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A FORCED ENTRY PLANNING MODULE FOR AMPHIBIOUS AIR ASSAULTS FOR THE JOINT WARFARE ANALYSIS EXPERIMENTAL PROTOTYPE

by

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The most difficult challenge in modeling and simulating modern warfare is the attempt to address every possible scenario, operating plan and tactic. One such model is the Joint Warfare Analysis Experimental Prototype (JWAEP) being developed at the Naval Postgraduate School. A scenario in which JWAEP needs further development is littoral warfare, which for the Marine Corps represents amphibious assault operations. An aspect of this type of warfare is referred to as "forced entry" when friendly ports are not available in the region of interest. Forced entry occurs by air, sea, or a combination of air and sea. Although these missions are very complex, mission planning is similar for each mode of transport. This thesis introduces the Forced Entry Planning Module (FEPM), a tactical decision planning aid, and offers a test of the conceptual amphibious air assault portion of FEPM using the most current United States Marine Corps amphibious air assault doctrine.

The concept was tested by constructing a standalone model, using deterministic combat attrition, to evaluate three potential methods for choosing a route to an amphibious air assault objective under uncertainty. The results indicated that each of the proposed methods predicted mission outcome under uncertainty with varying degrees of success. This limited testing has validated the concept of FEPM and the proposed methods. However, further refinement and testing is required before a final determination of which method is "best" for evaluating routes for forced entry missions is made.

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A FORCED ENTRY PLANNING MODULE FOR AMPHIBIOUS AIR ASSAULTS FOR THE JOINT WARFARE ANALYSIS EXPERIMENTAL PROTOTYPE

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ABSTRACT

The most difficult challenge in modeling and simulating modern warfare is the attempt to address every possible scenario, operating plan and tactic. One such model is the Joint Warfare Analysis Experimental Prototype (JWAEP) being developed at the Naval Postgraduate School. A scenario in which JWAEP needs further development is littoral warfare, which for the Marine Corps represents amphibious assault operations. An aspect of this type of warfare is referred to as "forced entry" when friendly ports are not available in the region of interest. Forced entry occurs by air, sea, or a combination of air and sea. Although these missions are very complex, mission planning is similar for each mode of transport. This thesis introduces the Forced Entry Planning Module (FEPM), a tactical decision planning aid, and offers a test of the conceptual amphibious air assault portion of FEPM using the most current United States Marine Corps amphibious air assault doctrine.

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DISCLAIMER

The reader is cautioned that the computer programs developed in this research may not have been exercised for all cases of interest. While every effort has been made to ensure that the programs are free of computational and logic errors, they cannot be considered validated. If desired, the source code, data files and output files can be made available upon request.

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EXECUTIVE SUMMARY

This thesis extends the Joint Warfare Analysis Experimental Prototype (JWAEP), a theater level combat model being developed at the Naval Postgraduate School, to represent littoral (near land) warfare. This concept has been a focal point of Navy and Marine Corps doctrine since the publication of "...From The Sea". An aspect of this type of warfare, along with the United States Army's Airborne mission, is referred to as "forced entry" when friendly ports are not available in the region of interest. Forced entry occurs by air, sea, or a combination of air and sea. Although these missions are very complex, mission planning is similar for each mode of transport. Information is gathered and conclusions are drawn for issues such as day or night execution, route selection, and the enemy air threat. This thesis introduces the Forced Entry Planning Module (FEPM), a tactical decision planning aid, and offers a test of the conceptual amphibious air assault portion of FEPM using current United States Marine Corps amphibious air assault doctrine. When complete, FEPM will conceptually have four submodules: air, sea, air\sea, and airborne.

A demonstration model was constructed to test FEPM for amphibious air assaults and evaluate the three proposed methods to plan this type of mission under uncertainty, the focal point of the JWAEP environment. The scenario used in this thesis to test FEPM is a hypothetical Korean MRC contingency operation. Soviet style weapon systems are modeled for use by the Red forces and current U.S. Marine Corps weapon platforms for amphibious air assaults are modeled for use by the Blue forces. The size of these forces are commensurate with a MRC sized contingency; for the Marine Corps, this consists of a Marine Expeditionary Force (MEF), which is approximately 1/3 of the total USMC end strength. FEPM for amphibious air assaults is designed to:

- be a stand-alone tactical decison aid that can be incorporated into JWAEP automated decision making.
- take the JWAEP state at snapshot(s) and evaluate it to determine the feasibility of amphibious air assaults.
- accurately reflect current United States Marine Corps Amphibious Assault Doctrine under uncertainty.
- provide JWAEP with an amphibious air assault course of action (COA) developed under uncertainty.
- deterministically adjudicate combat.
- predict mission success or failure under conditions of uncertainty about enemy force locations and strength.

To date, only a limited test has been performed on the three proposed methods for planning forced entry missions under uncertainty in FEPM. This was primarily due to the physical limitation of the software that was used in coding the demonstration model. However, the results thus far show that one of the three decision methods under uncertainty (Modal Method) has performed very well in planning forced entry missions in this limited test. Based on this result, the Modal method is considered to be the prime candidate for inclusion into the final version of FEPM that will eventually be incorporated in JWAEP. However, this was a limited test and should not be considered conclusive. Further testing of these methods in the JWAEP environment is the next immediate step in FEPM's development. Future versions of FEPM should focus on completing more of the forced entry sub-modules, such as a sea amphibious assault module. Finally, several areas for future research and experimentation are offered based on the results presented herein.

I. INTRODUCTION

A. OVERVIEW

The purpose of this thesis is to continue the development of the Joint Warfare Analysis Experimental Prototype (JWAEP), a theater level combat model being developed at the Naval Postgraduate School. An area of JWAEP that has limited representation is littoral (near land) warfare. Littoral warfare can be defined as comprising two segments of the battle space: seaward and landward. Seaward is that area from open ocean to the shore that must be controlled to support operations ashore. Landward is that area inland from the shore that can be supported and defended from the sea. This concept has been at the forefront of Navy and Marine Corps operations since the publication of "...From The Sea". [Ref. 1] An aspect of this type of warfare, along with the United States Army's Airborne mission, is referred to as forced entry when friendly ports are not available in the region of interest. Forced entry occurs in one or more of the following ways: by air, sea, or a combination of air and sea. The air portion of forced entry is further divided into amphibious air assaults and airborne assaults. Although these missions are very complex, the general mission planning is similar. Information is gathered and conclusions are drawn for issues such as day or night execution, route selection, and the enemy air threat. This thesis introduces the Forced entry Planning Module (FEPM), a tactical decision planning aid that can operate systematically or with a man-in-the-loop. Additionally this thesis develops and tests the amphibious air assault portion of FEPM using current United States Marine Corps amphibious air assault doctrine. When complete, FEPM will have four sub modules: air, sea, air\sea, and airborne.

B. BACKGROUND

1. JWAEP

JWAEP is an experimental theater level combat model under development at the Naval Postgraduate School. JWAEP's foundation is a combination of the Arc-Node Model (ANM), developed by the George Mason University for Argonne Laboratories, and the Future Theater-

Level Model (FTLM) developed by the Naval Postgraduate School. It is a 2-sided combat model that can be run interactively or closed. It represents ground and air maneuver through an arc-node network structure and a user defined air grid. At present only a limited representation of littoral warfare is available. [Ref. 2]

A key feature of JWAEP is its interactive command, control, communications and intelligence (C^3I) modeling, supported by the presentation of perception (derived from sensors) to a man-in-the-loop decision maker or model rule set. This allows *Red* and *Blue* players to develop a perception of the presence, absence, and size of combat units, derived from ground truth, at any arc or node they wish to view. The perception of the size of the force, derived from sensor input, is one way JWAEP introduces uncertainty. This uncertainty is presented to a player as the probability of seeing a particular force combination on any arc or node of interest. Presenting uncertainty through perception and C^3I is a realistic approach to modeling actual combat and is what makes JWAEP unique. It is important to note that entities, arcs, and nodes may be unknown to either side, allowing the attacker to conduct a surprise maneuver; this is particularly relevant for maneuver from the sea. [Ref. 2] Currently, the C^3I capability in JWAEP is being enhanced with decision rules. Decision rules are the focus of FEPM.

2. Forced Entry

Forced entry is loosely defined as an opposed insertion of a military force into an area of concern. In terms of planning, an example of this concept would be the operations in Haiti. A forced entry mission was planned, however the execution was more towards an entry of forces rather than an opposed insertion (forced entry). Army units were transported aboard Navy ships to the area of concern and then entered Haiti via helicopters. This type of operation also illustrates the importance of joint operations, whether they are amphibious or airborne assaults.

3. Model Scenario

The Korean Major Regional Contingency (MRC) scenario is used to evaluate FEPM. In the scenario, a Naval Expeditionary Force with embarked Marines enters the area and is given orders to pre-stage for amphibious operations. Commencement of amphibious operations will be at the discretion of the theater commander.

C. PROBLEM STATEMENT

JWAEP requires a representation of littoral warfare. A portion of littoral warfare for JWAEP will be contained in a decision aid such as the Forced Entry Planning Module. This thesis addresses the following questions regarding the initial implementation of the Forced entry Planning Module for amphibious air assaults:

- How should amphibious air assaults be planned under uncertainty?
- Is the accurate portrayal of current amphibious doctrine a constraint in planning under uncertainty?
- How should attrition of the forces be modeled?
- How should FEPM provide JWAEP with an amphibious air assault course of action (COA) under uncertainty?

D. RESEARCH OBJECTIVES

The primary objective of this thesis is to develop a tactical planning decision aid for the amphibious air assault mission portion of FEPM. In doing so it will present decision logic that answers the questions posed in the previous section. Chapter III provides insight into the implementation of the decision logic. The decision logic has been computerized and demonstrated using Borland's Pascal for Windows. The model was tested to determine whether FEPM for amphibious air assaults is suitable for incorporation into JWAEP. Results of these limited tests are documented in Chapter IV.

E. SCOPE

This thesis focuses on the amphibious air assault portion of the Forced Entry Planning Module. The data used in this model are consistent with representing a Marine Expeditionary Force for Major Regional Contingency requirements; however, the model can easily accommodate any size force.

F. ASSUMPTIONS

The following assumptions are made for this initial version of Forced Entry Planning Module:

- Blue forces will move as a single entity rather than in multiple waves.
- The air superiority value in the amphibious objective area is determined only by the air-to-air potential of each side. That is, surface-to-air threats are not factored into the air superiority value. This value is presently an input parameter.
- Naval forces' combat and attrition are not modeled .

G. LIMITATIONS

The following limitations exist in this version of FEPM:

- FEPM for amphibious air assaults is a deterministic model that takes snapshot looks over time at the JWAEP perception state.
- Attrition calculations performed by FEPM use data collected from the professional insights and judgements of officers attending the Naval Postgraduate School. These data have not been independently validated.
- Large data structures are not possible using the current version of Borland Pascal for Windows. This is not a limitation in the FEPM logic.

H. CHAPTER HIGHLIGHTS

Chapter II discusses the evolution of amphibious doctrine emphasizing the changes over the years and its current direction. It also reviews the background and structure of other amphibious air assault models, and then discusses the relevant features of JWAEP that are used by FEPM. Lastly, it outlines the general structure of FEPM. Chapter III provides a description of the methodology used in building the FEPM model. Model data structures, assumptions and the adjudication of combat are also covered in detail. Chapter III emphasizes planning and modeling under uncertainty consistent with JWAEP and methods to determine amphibious air assault COA(s). Chapter IV provides FEPM run analysis and results. The run procedures and uncertainty analysis are highlighted. Chapter V provides recommendations for future research and conclusions of this research effort.

II. BACKGROUND

A. EVOLUTION OF AMPHIBIOUS DOCTRINE

1. Origins

There is no specific date for the birth of amphibious warfare, but it is widely accepted that the idea of marines as seagoing soldiers dates back to the European naval wars of the seventeenth century. [Ref 3: p. 3] At first, these forces were used primarily aboard ships as defense forces. However, this role changed during the War of the Spanish Succession (1702-1713) where, for the first time, these detachments fought ashore as part of a landing force. [Ref 3: p. 4] In the ensuing years, the British capitalized on this new tactic and began building regiments of marines that would be used in their naval campaigns abroad.

The origin of amphibious warfare in the United States coincides with the birth of the United States Marine Corps, November 10, 1775. Since that date, amphibious warfare has traditionally been a Marine Corps mission that has evolved over the years. The remaining portions of this section are devoted to illustrating the historical development of amphibious doctrine, the command structure for amphibious operations and the different types of amphibious operations that the Marine Corps performs.

2. Historical Development of Amphibious Doctrine

Before 1930, amphibious doctrine was a developing theory that was broad and ill defined. The theory stemmed from the idea of establishing advanced bases from which the Navy and Marine Corps could operate. Several exercises were conducted between 1900 and 1920 to test the theory; they proved that amphibious operations worked quite well. However, the results were not formerly incorporated into Marine Corps doctrine until after World War I.

Following WWI, the Marine Corps advanced base mission began to fade. The Commandant of the Marine Corps, General John A. Lejuene, changed the Marine Corps mission from securing advanced bases to performing amphibious assaults. [Ref. 6] This change was in direct response to the Navy's War Plan ORANGE, which contained the Marine Corps Operation Plan 712. Plan 712 outlined the basic ideas and structure of amphibious assault doctrine, some of which are summarized below. [Ref 4]

- Transports should approach the transport area under cover of darkness off the beach area to permit an early morning landing.
- Naval gunfire should cover movement from ship-to-shore.
- Aviation should perform reconnaissance and close air support.
- Power craft should have mounted guns to protect troops during ship-to-shore movement.
- Demolition specialists should accompany the first wave in order to clear obstacles at the beach.

Unfortunately, after Operation Plan 712 was approved, no significant training events, other than a few cursory landing exercises, were held to evaluate the new doctrine. However, in 1927 the Landing Force (LF) role of the Marine Corps was officially recognized in a directive issued by the Joint Board of the Army and Navy.

> ...that the Marine Corps would provide and maintain forces for land operations in support of the fleet for the initial seizure and defense of advanced bases and for such limited auxiliary land operations as are essential for the prosecution of a naval campaign. [Ref 4: p. 6]

The task now facing the Marine Corps leadership was to produce doctrine to support this mission.

In 1934, the Marine Corps published the **Tentative Manual for Landing Operations** that was subsequently renamed Fleet Training Publication 167. [Ref 4] Training Publication 167 was a living document. Five major Fleet Landing Exercises (FLEX) were conducted which vigorously tested the new doctrine to identify "gaps and holes". After each FLEX, problems were addressed, new ideas were formulated and Training Publication 167 was revised. Fleet Training Publication 167 identified five crucial areas of amphibious doctrine.

- Command relationships
- Naval gunfire and aerial support
- Ship-to-shore movement
- Tactics of securing a beachhead
- Logistics.

These areas remained unchanged through the 1980's. However, technological advances have increased flexibility in terms of planning and execution, thereby improving the efficiency of amphibious assault missions. The following sections discuss the structure, command relationships and types of amphibious operations that are used today.

B. AMPHIBIOUS OPERATIONS

1. Structure

An amphibious operation can best be explained by the five phases of its operation: planning, embarkation, rehearsal, movement, and assault (PERMA). [Ref. 4] Figure 1 shows an organizational chart of command relationships for a Marine Expeditionary Unit (MEU), which is the smallest sized force that the Marine Corps uses for an amphibious operation. [Ref 4]

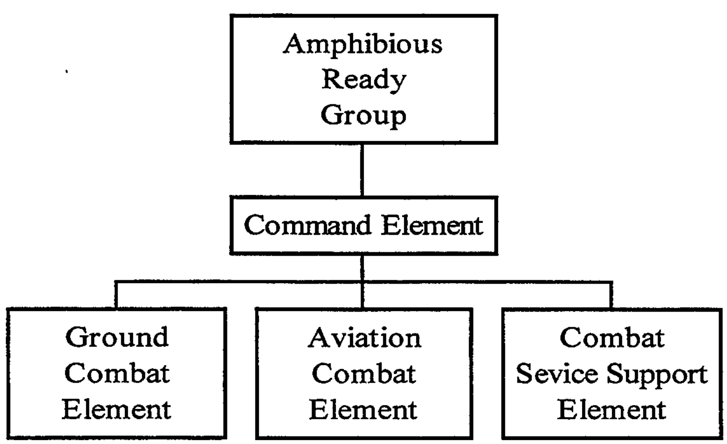

Figure 1: Marine Expeditionary Unit Organizational Chart

The composition of a typical MEU is as follows:

- a reinforced infantry battalion
- a reinforced helicopter squadron
- a combat service support element.

The largest composition of forces that would be used in amphibious operations is a Marine Expeditionary Force (MEF) which consists of the following:

- Marine Division
- Marine Aircraft Wing
- Force Service Support Group.

This size of force is planned for use in major regional contingencies as illustrated in this thesis. It is important to note that the command relationships and organization of a MEF follow the same basic structure of Figure 1. The single exception to Figure 1 is that the Naval Expeditionary Force (NEF) replaces the Amphibious Ready Group (ARG).

The major Naval vessels in an ARG consist primarily of amphibious ships, a few support ships, and escorts (such as Frigates and Destroyers). A NEF is a much larger force, typically composed of these major groups: [Ref. 7]

- Amphibious Group
- Aircraft Carrier Battle Group
- Cruiser Destroyer Group
- Mine Warfare Group
- Submarine Group
- Naval Special Warfare Group.

This force center of gravity for a NEF is the Aircraft Carrier Battle Group. The center of gravity for an ARG is the amphibious ships. In terms of amphibious shipping, a MEF is comprised of nine MEU's. It has been estimated that to transport a force of this size requires twenty seven amphibious ships.

2. Types of Amphibious Operations

There are four basic types of amphibious operations: [Ref. 4: pp. 9-10]

- Amphibious Assault - establishment of a Landing Force on a hostile shore.
- Amphibious Raid - establishment of a Landing Force on a hostile shore with a planned withdrawal after a period of time.
- Amphibious Demonstration - operation to deceive the enemy with a show of force to cause him to adopt an unfavorable course of action (feint).
- Amphibious Withdrawal - not predetermined but based on strategic or tactical considerations, conducted by a large force such as a division.

The focal point of this thesis is the amphibious assault. More detailed information concerning these missions is contained in the Amphibious Warfare School Non-Residents Course. [Ref. 4]

C. CURRENT DIRECTION OF AMPHIBIOUS WARFARE

The current direction of amphibious warfare stems from the Navy and Marine Corps White Papers "...From The Sea" and "Forward...From The Sea". [Ref. 1 and 5] The main point of these papers is that there is no longer "a global maritime threat". We have to focus "toward projecting power and influence across the seas in response to regional challenges". [Ref. 5] The Naval service must adapt to the changing world and find new and innovative ways to carry out this new mission. In the face of a decreasing budget and military downsizing, this is truly a difficult task. The following sections briefly illustrate some of the changes that have taken place in the Naval service, with specific emphasis on amphibious operations.

1. Doctrinal Changes of Amphibious Warfare

The White Paper "Operational Maneuver From The Sea (OMFTS)" best captures the shift in focus toward regional conflicts:

> OMFTS combines our freedom to maneuver from the sea with the tenets of maneuver warfare - tempo, momentum, strength against weakness, focus on the strategic objective - to decisively accomplish the mission. ...Operational Maneuver From The Sea is a concept for the projection of maritime power ashore. [Ref. 3]

OMFTS offers the amphibious assault commander a diversified and flexible approach to mission accomplishment. Commanders can now use any means available to reach an objective. This departure from past amphibious assault doctrine encourages more original thinking and freedom to maneuver in accomplishing the mission. There are several key principles, directions and functions of OMFTS. The key operational directions, relevant to this thesis, are addressed and presented below. However, to fully understand the concepts of OMFTS, a literature review by the reader is encouraged (See [Ref. 6]).

2. Key Operational Directions

As outlined above, OMFTS has several new directions for amphibious warfare: NEF Integration, Forcible Entry, and Other Expeditionary Operations. The focus on this section is the Forcible Entry direction of OMFTS and how it has and will continue to change amphibious doctrine.

In the past, amphibious operations were executed in three distinct phases: maneuver in ships, ship-to-shore movement and maneuver ashore. With OMFTS these phases have been reduced to just two: maneuvering in ships and landing force maneuver. The doctrine uses ships as assembly areas; transport areas (ship-to-objective area avenues of approach) as attack positions; and allows for the ground maneuver to begin from over-the-horizon. [Ref 6] The doctrine does not require that these forces will always have tactical surprise, but rather that these actions should deny the enemy early warning and reaction time. Beginning operations from over-the-horizon will force the enemy to defend a larger area, denying him the ability to mass his forces against these types of attacks. The major change in the doctrine is the freedom and flexibility to perform ship-to-objective maneuvers, allowing the commander to establish decisive combat power ashore in sufficient strength to ensure mission accomplishment. These ideas are reshaping amphibious assault doctrine and are the essential elements of maneuver warfare. The principles of maneuver warfare applicable to OMFTS are listed below: [Ref. 6]

- Focus on the strategic objective.
- Treat the sea as maneuver space.
- Create an overwhelming tempo.
- Generate momentum.
- Apply strength against weakness.
- Integrate all assets.
- Emphasize flexibility.
- Rely on intelligence.
- Key on advanced force operations.

This has been a brief examination of the new doctrinal ideas that the Navy and Marine Corps are presently addressing. This thesis attempts to use these new ideas in the development of FEPM for amphibious air assaults.

D. EXISTING MODELS

There are several models that incorporate or can incorporate amphibious operations in one form or another; however, not all of these models exhibit characteristics similar to the model developed in this thesis. This thesis reviews two models: The Marine Air Ground Task Force (MAGTF) Tactical Warfare Simulation (MTWS) [Ref. 7] developed by VisiCom Laboratories, Inc. and CUTTER, documented in a Naval Postgraduate School Master's Thesis by Captain Scott Shaw. [Ref. 8] Other major theater-level analytic simulations that do not presently model amphibious operations include TACWAR (Joint), CEM (Army), THUNDER (Air Force), and

ITEM (Navy). ITEM is currently developing an amphibious module, but information on the development was not available to the author. TACWAR has developed a naval module since this thesis was started; however, it does not reflect amphibious warfare *per se*.

1. Marine Air Ground Task Force (MAGTF) Tactical Warfare Simulation (MTWS)

MTWS is the next generation training system for the Marine Corps. This simulation is designed to support the training of tactical commanders and their staffs. It can also be used to supplement live exercises. MTWS is a highly data-driven man-in-the-loop model where the weapon systems and platform characteristics are parametrically represented. A unique feature of MTWS is its ship-to-shore capability in which the user is able to perform all amphibious warfare missions. The resolution is higher than JWAEP and it does not model uncertainty (uncertainty in this model is in the hands of the users). Data dependency and uncertainty introduced by a man-in-the-loop make this model unattractive for use in JWAEP.

2. CUTTER

CUTTER is an object oriented computer simulation that models a high-resolution ship-to-shore operation. [Ref. 8] It was designed to assist the Requirements, Plans and Programs Branch (RP&P) of Headquarters Marine Corps in comparing replacements for amphibious assault aircraft and vehicles used in ship-to-shore movement. CUTTER handles air, sea, and air\sea amphibious assaults for a MEU. It does not model attrition during the ship-to-shore movement of equipment and personnel. With several modifications, this model is an excellent candidate to be incorporated into JWAEP as an execution model of amphibious operations. An interface with the attrition model in JWAEP would have to be researched before possible incorporation. Detailed information concerning CUTTER can be found in Reference [8].

E. JOINT WARFARE ANALYSIS EXPERIMENTAL PROTOTYPE (JWAEP)

This section deals with JWAEP's design features that are relevant to FEPM. For a full description of JWAEP the reader should consult Reference [2].

JWAEP uses an arc-node structure to represent ground, air and littoral combat. Figures 2 and 3 show the ground/sea network and a user defined air grid, respectively. Information on the arcs and nodes will be made available to FEPM. It is important to note that the air assault forces in FEPM will "travel" to their objectives by flying along the ground arc-node structure rather than the air grid structure. This is consistent with the model of helicopter assault operations developed for JWAEP by CPT Hume. [Ref 9] Since the aircraft involved in this type of mission seek the cover and concealment afforded by low flight, this decision to fly along the ground network is reasonable. Further, these aircraft are more susceptible to small arms fire, AAA and man-portable missiles than the larger scale surface-to-air missile threat with which the air grid is primarily concerned. These ground routes or paths are generated either manually or automatically. In manual generation the user chooses the route; the automatic generator chooses one "least cost" path between nodes. Ground attrition is handled through the Combat Sample Generator/Attrition Calibration (COSAGE/ATCAL) process developed by the Army's Concepts Analysis Agency. The air network, called the air grid, is a user-defined network that overlays the ground network discussed above. Air routes or paths are generated by a path selection algorithm that minimizes threat exposure while maintaining range constraints of the aircraft. [Ref. 2] Air attrition is handled by algorithms developed for the United States Air Force THUNDER model.

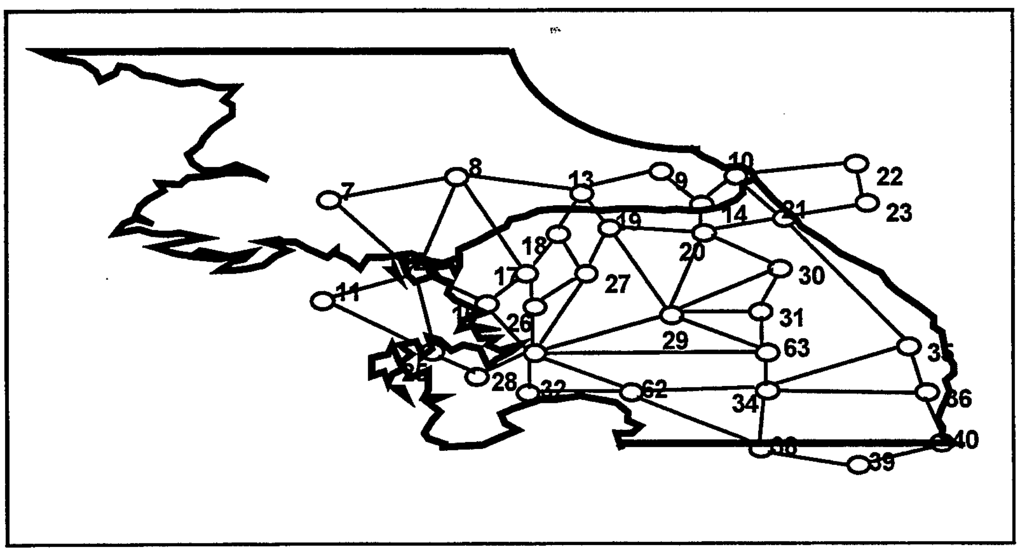

Figure 2: Example of the Ground Arc-Node Network

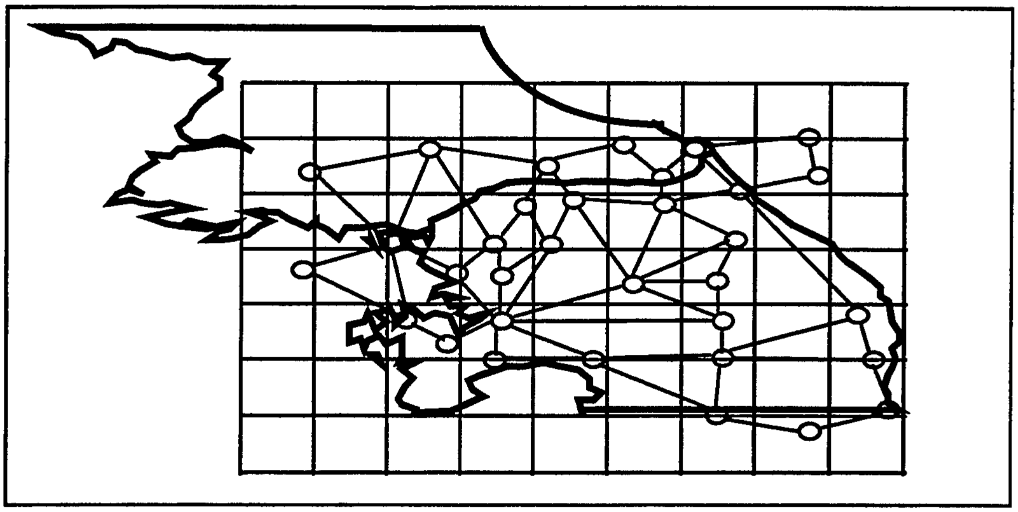

Figure 3: Example of an Air Grid Overlay on the Ground Arc-Node Network

A unique feature of JWAEP is that each arc and node contains a perception of each side as obtained through sensors (combat, network, and scheduled) and situation reports. These perceptions are updated (using Bayesian procedures [Ref. 2]) at user defined intervals, typically every 2 hours. This explicit quantification of perception is one way that uncertainty is introduced in JWAEP. This treatment of uncertainty is what makes JWAEP different from other theater level models and makes it more difficult to develop new algorithms such as FEPM. An example illustrates how perception is quantified. Suppose that one unit is on a node (ground truth). Assume that up to three units could occupy this node and no information is available (worst case) concerning the number of units occupying the node. Complete uncertainty is often modeled by a flat prior; thus an equally likely chance of 0, 1, 2, or 3 units occupying this node is assumed. Complete uncertainty further implies that there is a 25% chance of seeing any of the combinations of the units on this particular node. Therefore, under complete uncertainty there is a 25% chance of a command successfully predicting the correct unit size and 75% chance that the prediction is wrong for this example. This small example illustrates that when little or no information exists, planning and executing missions become increasingly difficult. However, this is exactly how real world missions are planned and executed when there is a lack of information. More often than not, commanders use a "best guess" when presented with this situation. As more information becomes available, a commander will be able to make better decisions when planning and executing missions. JWAEP was developed to address this issue and closely models real world mission planning and execution. Detailed information concerning the current status of JWAEP's perception, fusion, and communication algorithms are available in Section VIII of reference [2].

F. FORCED ENTRY PLANNING MODULE (FEPM)

FEPM has been developed to partially meet JWAEP's requirement for a representation of littoral warfare. FEPM was then expanded to include heliborne or airborne insertions because (by definition) they deliver a force into an area of concern or interest to the United States (forced entry). FEPM is designed to provide JWAEP with a planning decision algorithm that will address forced entry missions. It addresses the planning of an amphibious air assault by using the ideas of OMFTS outlined in Section C. FEPM for amphibious air assaults is designed to:

- be a stand-alone tactical decison aid that can be incorporated into JWAEP automated decision making.
- take the JWAEP node perception state at snapshot(s) and evaluate it to determine the feasibility of amphibious air assaults.
- accurately reflect current United States Marine Corps Amphibious Assault Doctrine under uncertainty.
- provide JWAEP with an amphibious air assault course of action (COA) developed under uncertainty.
- deterministically adjudicate combat.
- predict mission success or failure under conditions of uncertainty about enemy force locations and strength.

FEPM for amphibious air assaults requires input from JWAEP. This model does not interface directly with JWAEP but uses input files which can be constructed from JWAEP outputs. Examples of input data are: potential objectives for amphibious assaults, routes to those objectives, and perceptions of enemy forces on the objectives and their routes. This list is not all-inclusive and is expanded upon in Chapter III.

The model's decision logic, proposed interaction with JWAEP, data base manipulation and results are demonstrated using Borland Pascal for Windows©. This model provides predictions of mission success\failure and other parameters such as remaining ground force size at the objective under uncertainty. If the mission is a predicted success, FEPM will (notionally) send to JWAEP a viable amphibious air assault COA. The main challenge for FEPM is to produce reasonable decisions for amphibious air assaults under uncertainty.

III. METHODOLOGY

A. FORCE ENTRY PLANNING MODULE

1. General

The Force Entry Planning Module (FEPM) is a stand-alone deterministic planning model used to develop amphibious air assault courses of action (COA) under uncertainty for JWAEP. JWAEP will provide input data to FEPM. Assuming that a US (Blue) force entry is being executed, the input data required for the Blue force include their perception of the state of the Red combat units for all of the arcs and nodes on possible routes to the objective. FEPM uses these data to execute algorithms that adjudicate combat engagements and determine whether the mission is a success or failure. The algorithms also use data files that contain information such as probability of kill for each weapon system, the number of weapon systems, and their rules of engagement. The data used in this thesis were obtained from current United States Army and Marine Corps doctrinal publications and the professional insights and judgments of students attending the Naval Postgraduate School whose warfare specialties are applicable to these mission types.

A mission in FEPM is considered a success if the Blue force is not reduced below a predetermined percentage (breakpoint) of its starting size; otherwise, the mission is a failure. FEPM's output currently reports mission outcome (success or failure), remaining Blue forces and the time required to reach the objective. It should be noted that FEPM's output is flexible in that it can be reconfigured to meet JWAEP's input requirements.

An amphibious air assault mission is primarily flown at low altitudes. As a result, (due primarily to the type of weapon systems employed by Red) this thesis assumes that Red forces on nodes and arcs adjacent to, but not on, the route of flight (which is overlaid on the existing ground network) have little or no effect on mission results. With the exception of the ZSU-23-4, these weapon systems are primarily line of sight (LOS) for acquisition and targeting. Additionally, all of these systems are limited in range and their effectiveness is severely degraded when targeting below 200 feet above ground level. Therefore, FEPM does not take into account the potential combat power of the nodes and arcs adjacent to the routes to the objectives. However, research into this area is underway and Captain Nick Slavik addressed some of these issues in his Master's thesis. [Ref. 10]

Finally, FEPM currently makes decisions under uncertainty by evaluating the expected attrition at each node (calculated deterministically) to the attacking Blue force, using a decision rule to select the Red force, and then comparing these values to predetermined breakpoint values discussed later in this chapter. As the Blue force attacks (traverses over the potential route), "go / no-go" decisions are made at each node based on the combat attrition to Blue. If Blue reaches the potential objective before it reaches its breakpoint values, the route is passed on to JWAEP as viable for that objective. In order for FEPM for amphibious air assaults to be incorporated into JWAEP, it must predict mission outcome under uncertainty successfully, meaning that a correct decision of "no-go" is preferred to an incorrect "go" decision for any potential route.

2. Proposed Interaction with JWAEP

FEPM's flow of information and interaction with JWAEP are depicted in Figure 4 on the following page. The dashed lines represent the paths along which JWAEP and FEPM would eventually interact.

a. JWAEP Inputs to FEPM for Amphibious Air Assaults

There are four inputs that FEPM needs from JWAEP to execute its planning algorithms:

- The starting size of the Blue force.
- The state of air superiority in the local area.
- The routes to the objective (these routes contain C^3I perceptions of the Red force which serve as the Red force input).
- The amphibious air assault objective.

Sample files have been included in the proposed FEPM demonstration model that simulate input files from JWAEP.

The composition of the sample files is consistent with the Korean MRC scenario. The starting Blue force size is provided as Table 1. The equipment types were obtained from the "Marine Air-Ground Task Force: A Global Capability", FMFRP 2-12. [Ref. 12] The aircraft listed are the same as those in a Marine Expeditionary Force (MEF). This list does not include any carrier or land-based air assets that would complete the actual air component of a MEF.

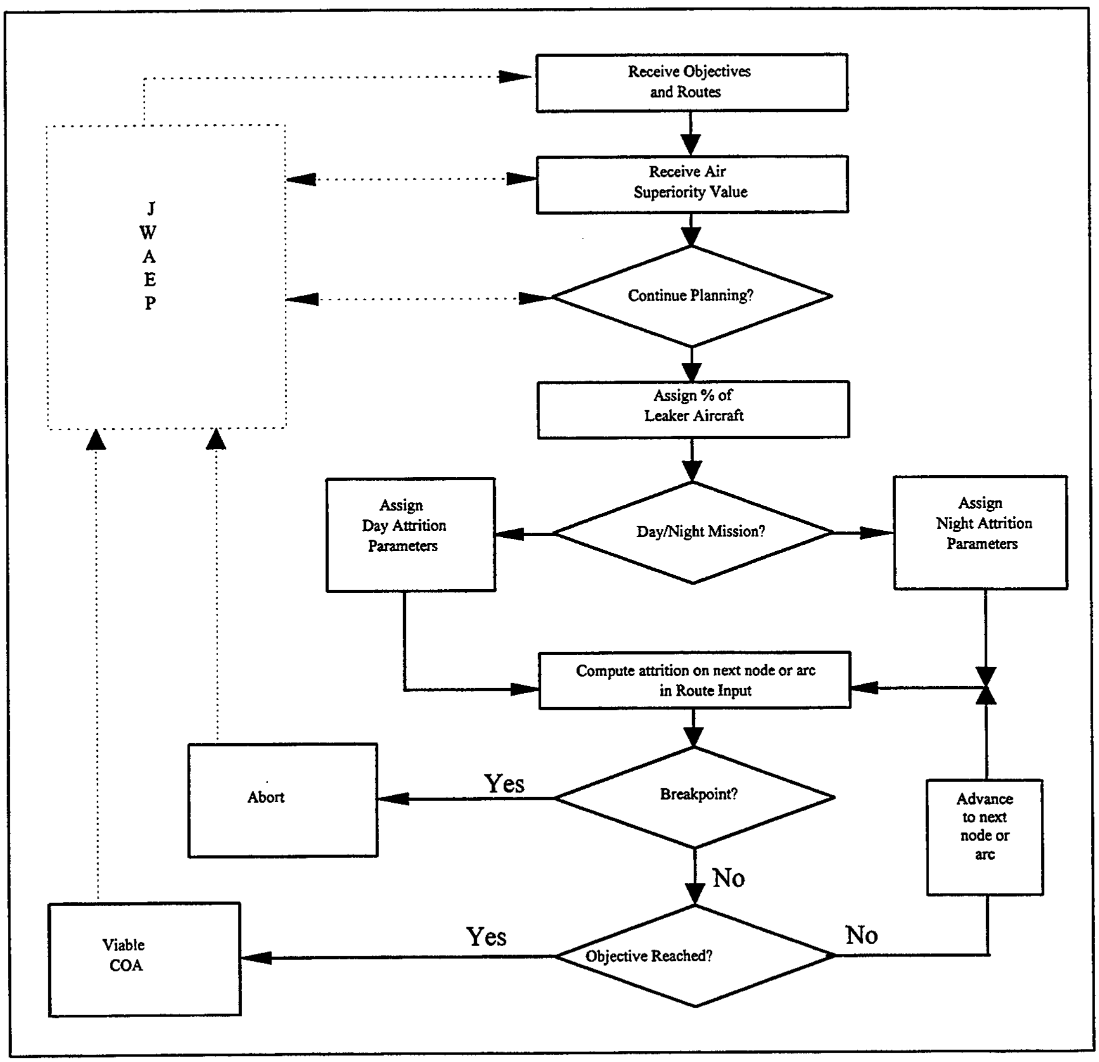

Figure 4: Force Entry Planning Module Flow Chart

Aircraft Type	AV-8B	CH-46E	CH-53A\D	CH-53E	AH-1W	UH-1N
Quantity	60	60	12	32	24	24

Table 1. Partial Air Unit List of a Marine Expeditionary Force

The Blue force air superiority value is determined by comparing the Blue and Red forces actual air threat strengths at each node and arc. Perceptions are not presently used as JWAEP does not have an air threat perception. This can be modified when JWAEP is improved. There are three categories of air superiority in this thesis; low, medium and high. These categories determine the number of "leaker" aircraft that can engage Blue assault force units. A "leaker" aircraft is defined as a Red aircraft that penetrates Blue's air defenses and is able to engage the air assault force. Table 2 lists the air superiority values and the percentage of leakers assumed for each. These percentages are applied to the number of "mission capable" aircraft that Red has in the amphibious assault operating area, which is an input to FEPM. A "mission capable" aircraft is an aircraft that can perform the required mission; this category does not include those in maintenance or combat losses. This number is typically reported as the material readiness of that particular unit and is contained in JWAEP's perception database. The air superiority value does not currently exist in JWAEP, but can be derived from the number of sorties flown in the area being considered for an amphibious assault. This value can be added to JWAEP's strength categories, currently being evaluated in the ongoing research into future versions of JWAEP.

The result of the two steps (receive air superiority value and assign % of leaker aircraft) from Figure 4 gives the number of Red aircraft to be used in the adjudication of combat. This number is presently fixed (deterministic) and is rounded down from the product of the Red aircraft at a node and the percentage of leakers.

Blue Force Air Superiority	Low	Medium	High
Red Leaker Percentage	90%	50%	10%

Table 2. Air Superiority Values with Associated Leaker Percentages

The final inputs that FEPM receives from JWAEP are possible routes to the objectives. These routes are generated by JWAEP's modified Dykstra's Least Cost Path algorithm and contain Blue's perception of Red's forces at each node and arc. [Ref. 2]

This file would have to contain at a minimum the following information:

- Node identification number.
- Distance to the next node or final objective.
- Blue's perception of the type and number of Red force units at each node along the route.

b. FEPM for Amphibious Air Assaults Output to JWAEP

The structure of FEPM allows a variety of outputs to JWAEP: remaining Blue force size, Blue force losses, and mission success or failure. This list is not all-inclusive and can be modified to meet JWAEP requirements. The FEPM reports the probability of mission success from the standpoint of 1) reaching the objective while evaluating a potential route (accomplished when the remaining Blue Force size is greater than the breakpoint values in Table 3), or 2) determining that the route/objective is not reachable (remaining Blue force size is less than the values in Table 3). This concept is developed further in the following sections.

B. DATA

FEPM for amphibious air assaults uses several different data files and parameters when executing the planning algorithm. These data files include Red and Blue force unit and equipment types, probability of kill matrices, fire allocation tables and Blue force mission breakpoint parameters.

1. Blue Force Data File and Breakpoint Parameters

The Blue force data file maintains the current status of the Blue force units within FEPM. Also included in the data file are breakpoint values for the force. Each weapon platform has a breakpoint and, if violated, the algorithm will stop and report that this particular mission was a failure. Breakpoint values are expressed as the percent of losses from the Blue force starting size. The Blue force weapon platforms and their assumed breakpoint values are listed in Table 3.

Weapon Platform	CH-46	CH-53	AH-1W	UH-1N	AV-8B
Breakpoint	50%	50%	60%	60%	40%

Table 3. Breakpoint Percentages for Blue Weapon Platforms

2. Red Force Data File

The Red forces used in FEPM for amphibious air assaults fall into one of five categories: infantry, mechanized, armor, air defense and aircraft. The sizes of these units are comparable to a brigade or an air group. The model is only concerned with the Red force weapon systems and platforms that can attrite the Blue force weapon platforms (Table 1), with specific emphasis on the troop carriers. From the JWAEP unit database, three weapon systems were chosen and modeled in FEPM. The number of the Red force ground weapon systems that would be found in a typical brigade sized unit are provided in Table 4. For FEPM, three aircraft types are used: MIG 21, SU-25 and SU-27. These aircraft are flown in flights of two and will not exceed eight (8) of each type on a given node; the number actually used in combat adjudication depends on the percent of leakers computed. For the test cases, the number and type of Red aircraft for each node were assigned at random.

Red Weapon System	Infantry	Mechanized	Armor	Air Defense
ZSU 23-4	2	4	4	8
S - 60	2	4	4	4
Man-Portable SAM	50	30	30	25

Table 4. Red Weapon Systems and Quantities per Unit Type

3. Probability of Kill Calculations and Matrices

Probability of kill (P_K) calculations in FEPM is defined as the product of the following four probabilities:

- probability of detection (P_{Det}) is the probability of a Red type unit/platform detecting a Blue platform and vice versa
- probability of shot given detection ($P_{Shot/Det}$) is the probability that when a unit/platform (Blue or Red) detects an opposing unit that it fires on that detected unit
- probability of hit given shot ($P_{Hit/Shot}$) is the probability that the firing unit/platform hits the unit/platform that it is firing at
- probability of kill given hit ($P_{K/Hit}$) is the probability that the unit/platform given that it has been hit is killed. It is assumed that $P_{K/No\ Hit} = 0$ (no collateral damage)

Therefore, the probability of kill (P_k) equation is as follows:

$$P_{K\,ij} = P_{Det\,i,j} \times P_{Shot/Det\,i,j} \times P_{Hit/Shot\,i,j} \times P_{K/Hit\,i,j} \qquad (1)$$

where,

$i \equiv$ weapon system type (killer)
$j \equiv$ weapon system type (victim)

This equation is also used to determine the probability that an aircraft delivered weapon can kill an aircraft delivered weapon. Tables 5 and 6 are the P_K matrices for the Blue and Red forces, respectively. For the initial (demonstration) model, the values for $P_{K/Hit}$ and $P_{Shot/Det}$ are equal to 1.0 for all *i,j*. The remaining values (P_{Det} and $P_{Hit/Shot}$) are derived from the author's experience and that of other students attending the Naval Postgraduate School. To simplify, only one shot is assumed by each weapon system on average. The probabilities of kill were based on this assumption. These shots are also distributed over the target without overlap (implied in equation (1)). This is a simplistic model but it is sufficient to test FEPM and examine differences between decision rules under uncertainty.

Weapon System		Probability of Detection		P Hit/Shot	Probability of Kill ($P_{kill/hit}$)	
j (killer)	*i (victim)*	Day	Night		Day	Night
AV-8B	ManPortable	0.3	0.1	0.75	0.225	0.075
	S-60	0.5	0.25	0.8	0.4	0.2
	ZSU 23-4	0.5	0.25	0.8	0.4	0.2
AH-1W	ManPortable	0.4	0.15	0.8	0.32	0.12
	S-60	0.4	0.15	0.85	0.34	0.128
	ZSU 23-4	0.4	0.15	0.85	0.34	0.128
UH-1N	ManPortable	0.35	0.15	0.7	0.245	0.11
	S-60	0.35	0.15	0.75	0.263	0.113
	ZSU 23-4	0.35	0.15	0.75	0.263	0.113

Table 5. Blue Force Probability of Kill Matrix

Weapon System		Probability of Detection		P Hit/Shot	Probability of Kill ($P_{kill/hit}$)	
i (killer)	*j (victim)*	Day	Night		Day	Night
MIG 23	Transports	0.3	0.25	0.5	0.15	0.025
	Helo Escorts	0.3	0.05	0.5	0.15	0.025
	FW Escorts	0.5	0.05	0.7	0.35	0.175
SU 25	Transports	0.3	0.25	0.5	0.15	0.075
	Helo Escorts	0.3	0.15	0.5	0.15	0.075
	FW Escorts	0.5	0.15	0.5	0.25	0.125
SU 27	Transports	0.3	0.25	0.5	0.15	0.075
	Helo Escorts	0.3	0.15	0.5	0.15	0.075
	FW Escorts	0.5	0.15	0.8	0.40	0.2
ManPortable	All	0.5	0.25	0.7	0.35	0.175
S-60	All	0.5	0.25	0.6	0.30	0.15
ZSU 23-4	All	0.5	0.25	0.7	0.35	0.175

Table 6. Red Force Probability of Kill Matrix

4. Fire Allocation Tables

Fire allocation is the process of assigning firing rules to weapon systems/platforms when they engage other weapon systems/platforms. These rules are expressed as percentages. An example of a fire allocation rule for a SAM site is to expend 45 percent of fires against helicopters, 25 percent against fighters, and 30 percent against bombers. Actual fire allocation rules are much more complex and may have additional constraints based on the weapon system/platform reliability and the given Rules of Engagement. For this model, each side has fire allocation rules and Tables 7 and 8 represent those rules for the Blue and Red forces, respectively.

Blue Force Fire Allocation Table			
Red Weapon Systems			
	ManPortable	S-60	ZSU 23-4
Rule	33%	33%	33%

Table 7. Hypothetical Blue Force Fire Allocation Rules

Red Force Fire Allocation Table					
Blue Weapon Systems					
	CH-46E	CH-53	AH-1W	UH-1N	AV-8B
Rule	20%	20%	20%	20%	20%

Table 8. Hypothetical Red Force Fire Allocation Rules

For this model, we use the simplest case of spreading allocation equally among Blue and Red . These values represent the percentage of munitions expended to engage a given weapon system. For instance when Blue is attacking Red, Blue weapon systems will allocate their fires equally among the Red weapon systems present. Due to the complexity that fire allocation rules can present, different fire allocation rules for each individual weapon system were not modeled in this thesis.

C. ASSUMPTIONS

The following assumptions are made for this model:

- Blue force breakpoints are used to determine mission status: success or failure.
- Carrier air, TACAIR, and Naval supporting arms (cruise missiles, naval gunfire) are not modeled.
- Naval Expeditionary Force approach routes are not known to the Red force; hence, detection of the NEF is not modeled. However, the contribution from air is implicitly modeled in part through the air superiority values.
- Observations by the Blue Force of the Red force units and vice versa are independent.

These assumptions were made to reduce the number of variables to a manageable number while still permitting FEPM to be adequately evaluated. FEPM plans potential amphibious air assault missions, given the inputs described above. It does not model the arrival of the Naval Expeditionary Force (NEF) into the theater's amphibious operation areas. Modeling seaborne Naval forces is not considered within the scope of the FEPM amphibious air assault model. If desired, this model could be adapted such that once the NEF force is detected, Red forces are able to react based on their perception of the NEF's Course of Action (COA). This would allow the Red force to choose a COA to reinforce positions in defense of an anticipated amphibious assault. However, with the new doctrine of OMFTS (outlined in Chapter 2), the NEF force would commence an assault from over-the-horizon. Thus, the Red force's detection of the NEF is unlikely unless they possess strategic systems such as satellites. Even if the Red force had conventional resources such as air reconnaissance, submarines, and patrol boats, the NEF's true composition and movement would only, at best, be an estimate. Moreover, the options available to the NEF (which is capable of long range off-shore attacks) make the Red force's decision to reinforce more difficult because there is a larger potential threat area to defend.

D. DEALING WITH UNCERTAINTY

1. Why?

The power of JWAEP is in its C^3I modeling. It accomplishes this through the presentation of a perception derived from sensors. As explained in Chapter 2, "these sensors can be assigned to units, the network and to footprints assigned to the terrain to develop a separate, stochastic perception of ground truth" for either side [Ref. 2]. If the Force Entry Planning Module for amphibious air assaults is to be suitable for incorporation into JWAEP, it has to deal with and plan accurately under uncertainty.

2. Generating Uncertainty for Testing FEPM

FEPM will receive the uncertainty perception information from JWAEP. The problem for testing FEPM is to derive perception data similar to that which would be obtained from JWAEP. To accomplish this, the perception data generated must relate to ground truth as they do with JWAEP. One possible way to generate perception data in the demonstration model is to arbitrarily assign probabilities to randomly selected Red force combinations (on nodes and arcs) and test FEPM using this data. The problem here is that the relationship between the perception and ground truth (on the nodes and arcs) is lost. Therefore this "random" assignment of probabilities and Red force combinations is not suitable for testing FEPM.

A better approach, the one chosen for this thesis, deals with generating uncertain perception probability vectors from Red ground truth. Since the goal of FEPM is to accurately predict mission success under uncertainty as represented in JWAEP, we must investigate the effects that different unit combinations have on predicting mission success. For example, suppose the ground truth of an arbitrary node along a potential route to an amphibious assault objective is as follows:

$$\text{GroundTruth} := \begin{bmatrix} 1 \\ 0 \\ 2 \\ 2 \end{bmatrix} \quad \begin{bmatrix} \text{Infantry} \\ \text{MechInf} \\ \text{Armor} \\ \text{ADA} \end{bmatrix} \quad \text{with the unit type shown.}$$

If we consider a total of 3 units possible of each type (12 total) at the node, there are $4^4 = 256$ possible unit perception vectors, each representing one combination of units. JWAEP will determine a probability for each of the 256 possible vectors based on the inference process discussed in the JWAEP documentation. [Ref. 2] Any set of 256 numbers summing to 1 is possible, although under conditions of good sensor coverage the ground truth vector and others close to it will have the largest probabilities associated with them and small probabilities will be associated with other vectors.

To test FEPM under similar conditions, a set of vectors were chosen that have high, medium and low perception uncertainty and bias (accuracy) relative to the ground truth. There are $3^2 = 9$ possible combinations, an example of which would be high uncertainty paired with low bias. For the tests described in this thesis a pairing is used for an entire route (e.g., high uncertainty, low bias route). Additionally, the special case vectors of certain ground truth, flat prior and other combinations not already mentioned were also included in the test. A more detailed explanation and complete listing of the vectors used to test FEPM are contained in the following chapter and the appendix. The perception vectors in Appendix A were assumed because the demonstration model can not duplicate the JWAEP environment or the sophisticated inference process.

3. Predicting Mission Outcomes Under Uncertainty

Predicting mission outcomes under uncertainty is a difficult task, especially with varying degrees of uncertainty. Uncertainty is based on the information or lack thereof at the time when a decision has to be made. This information could be perfect, in that it is based on factual data, or purely speculative, for which none of the data can be substantiated, or it can have a mix of both. FEPM considers several ways to address the difficulties with predicting mission outcomes under uncertainty. These are certainly not all-inclusive and are by no means the final answer. JWAEP quantifies the uncertainty in the information about an enemy through the vector of probabilities of unit numbers and types at each node. FEPM attempts to address uncertainty by making a decision based on this vector in three ways: using the mode of the perception probabilities, using the three largest perception probabilities, and using all of the perception probabilities. The actual decision mechanism to use in conjunction with JWAEP can be chosen by the user. These approaches are further explained in the following paragraphs. The extreme cases of predicting under uncertainty (having perfect information or no information) are also addressed below.

a. At the Extremes

There are two extreme cases when dealing with the C^3I perception. The first is perfect information (ground truth). In this case, FEPM for amphibious air assaults should predict correct mission results with a probability of 1. However, FEPM takes a snapshot look at the current JWAEP state, which is based on perception and evaluates the route with this information. Because of this, information contained in the current JWAEP state includes previous information through the use of a prior distribution, which will result in a some degree of uncertainty (unless the prior is also ground truth) even when the current information is, in fact, ground truth. JWAEP uses ground truth only to adjudicate combat between units. FEPM's deterministic structure does not allow for the explicit use of *a priori* information; instead it adjudicates combat by computing the expected Red force averaged over the current state perception probability. If the perception is the same as ground truth, FEPM exactly predicts the outcome, which is the same as the ground truth adjudication in JWAEP.

The second extreme case is when there is no information at all. This case needs to be considered because there are times when missions must be executed even in the face of total uncertainty, although these are very rare. Complete uncertainty is represented by a flat (non-informative) prior; thus, there is an equally likely chance of seeing any possible combination of

Red forces on a given node or arc. Correctly predicting results in this case is extremely difficult. A tactical mission of this size and scope would require more information. Therefore, FEPM currently is coded to send a "No-go" message to JWAEP advising that this mission should not occur due to lack of information. However, if the mission has to be executed, FEPM evaluates all possible routes to the objective using the weighted sum method (the only method that can handle this situation) and recommends the route that yields the least amount of attrition using the Blue force breakpoints discussed in Section B.1 of this chapter.

b. Using the Largest Probability (Mode)

Using the largest probability (mode) of the perception vector yields a single Red force composition vector on a given node or arc along the route to the objective. This vector is then assigned a probability of one (normalized with itself) for use in the adjudication process of FEPM. Once FEPM has computed expected combat outcomes for each node or arc along a possible route, or a Blue force breakpoint has been reached, the mission outcome is sent to JWAEP. The simplicity of this approach is also its weakness. By selecting only one Red force combination vector, the successful prediction of mission results will depend on how well the mode agrees with ground truth. This agreement will increase as sensor capabilities increase. Likewise, as the sensor capabilities decrease, there is a greater chance that the prediction will be incorrect. Difficulties with this method arise when perception probabilities for different unit combinations equal each other. In this case, the demonstration model defaults to the first largest probability that it encounters, which may or may not be near ground truth. [1] The analysis of this method is presented in Chapter IV.

c. Using the Three Largest Probabilities

Another approach uses the average of three largest probabilities to predict combat outcomes. The perception probability vector is altered so that only the three largest (in probability) combinations are positive, and the others have zero probability. The altered vector is normalized so the three remaining probabilities sum to one. The Red force used to compute

[1] The ordering is arbitrary based on how JWAEP is coded.

attrition is the weighted sum of the three force combinations. No transformation is needed if there are three or less non-zero Red force perception vectors on a given node or arc. By using the three largest probabilities, there is a greater chance that the algorithm includes the actual ground truth vector, thus more "realism" might be expected in the planning process. In cases where the total number of non-zero vectors is less than or equal to three, the algorithm will always contain the actual ground truth vector. However, this approach has similar problems to the largest probability (modal) method when there are many perception vectors of roughly equal probability. The analysis in Chapter IV shows how well this method performs under uncertainty.

d. Using all of the Perceived Probabilities

This approach takes all data generated at a node or arc and runs the assumed Red force, which is the weighted sum of all combinations (weighted by the probabilities - PS_m vector), through FEPM. The result from this run is used when adjudicating combat at each node or arc (remembering that FEPM's current limitation precludes evaluating every Red force combination). If the number of vectors with non-zero probabilities is very small (less than or equal to three), this method will produce the same results as in the largest three method. The analysis and performance of this method is shown in Chapter IV.

E. ADJUDICATION OF COMBAT

This section discusses the combat adjudication process of FEPM for amphibious air assaults. The order of combat in FEPM for amphibious air assaults is air-to-air, air-to-ground, and ground-to-air. Simultaneous combat at nodes or arcs is not possible due to FEPM software limitations. This limitation is not present in JWAEP.

The attrition of forces is based on the expected number of kills that weapon system i can achieve against weapon system j and vice versa at each node and arc. These equations take into account fire allocation rules, probabilities of kill, Red and Blue force size and composition, and the uncertainty surrounding what weapon systems are located at the node or arc.

Let

c = Force combination
m = Node\Arc identification number
i = Killer
j = Victim
t = Time, $t \geq 1$
$PS_m(c)$ = Probability of seeing a particular unit Red force combination *c* at node *m*
BFA_{ij} = A matrix representing fire allocation rule for Blue Force weapon platforms (Table 7)
RFA_{ij} = A matrix representing Fire allocation rule for Red Force weapon system (Table 8)
$BF_m(t)$ = A vector of the total Blue Force weapon platforms on node\arc *m* at time *t*
$BA_m(t)$ = A vector of the Blue Force weapon platforms (subset of BF) that can attrite Red weapon systems on node\arc *m* at time *t*
$RF_m(t)$ = A matrix of Red Force weapon systems on node\arc *m* at time *t* after the decision rule is applied, which sums the weapons found in one or more weighted unit combinations
Pk_{ij} = Probability of kill matrix of weapon system type *j* (victim) by weapon system type *i* (killer) (Eq. 1)
$W_m(t)$ = A vector of Red weapon systems on node\arc *m* at time *t*
$X_m(t)$ = A vector of Blue weapon platforms killed on node\arc *m* at time *t*
$Y_m(t)$ = A vector of Red weapon systems killed on node\arc *m* at time *t*

To illustrate the adjudication process, an example is offered. The basic scenario will be a day engagement at an arbitrary node *m* along a potential route to an amphibious air assault objective. The variables described above are used to define and introduce the equations used by FEPM. Any additional information will be defined and or clarified when appropriate.

The attrition will be illustrated using the modal method. Recall the earlier discussion on generating uncertainty where possible unit combinations were created with each having an associated perception. For this example consider the following observation (which is a subset of the 256 total possible combinations, which is why the perception vector probabilities do not sum to one) on arbitrary node *m* at time *t*.

We define $PUnit_m$ as the matrix of unit combinations with probabilities PS_m at a node *m*. Each row *r* of PUnit represents the probability that *i* units of type *r* (*r* = 0,..,3 for the example where 0 = Infantry, 1 = Mechanized, 2 = Armor, and 3 = Air Defense) are present for i = 0, 1, 2, 3.

1. Modal Method

$$PUnit_m := \begin{bmatrix} 0 & 1 & 2 & 0 \\ 1 & 1 & 0 & 0 \\ 2 & 0 & 0 & 1 \\ 1 & 2 & 0 & 2 \\ 0 & 0 & 2 & 1 \\ 0 & 0 & 1 & 1 \end{bmatrix} \quad \text{with associated perception probabilities} \quad PS_m := \begin{bmatrix} .35 \\ .4 \\ .1 \\ .05 \\ .03 \\ .02 \end{bmatrix}$$

For example, there is a 35% chance that node m contains 0 infantry, 1 mechanized, 2 armor and 0 ADA units. To analyze using the modal method, we select the row with the highest associated probability. The associated unit combination is the number of Red units of that type assumed to be present. For convenience, define a vector Red_{Mode} which denotes the most likely force combination on the node. Note that it has dimension 4 x 1. From $PUnit_m$ and PS_m, we see that the mode is:

$$Red_{Mode} := \begin{bmatrix} 1 \\ 1 \\ 0 \\ 0 \end{bmatrix} \quad \text{with associated unit types} \quad \begin{bmatrix} \text{Infantry} \\ \text{Mechanized} \\ \text{Armor} \\ \text{AirDefense} \end{bmatrix}$$

The variable RF is the Red force weapon matrix that has dimension row 1 (weapon type) by column r (unit type). In this example, RFm(t) is as follows, where weapon types (rows) are 0 = ZSU-23-4, 1 = S-60, and 2 = Man-portable SAM. Unit types are as defined above.

$$RF_m := \begin{bmatrix} 2 & 4 & 4 & 8 \\ 0 & 0 & 0 & 0 \\ 50 & 30 & 30 & 25 \end{bmatrix}$$

Then if we define $ERed := RF_m \cdot Red_{Mode} = \begin{bmatrix} 2 & 4 & 4 & 8 \\ 0 & 0 & 0 & 0 \\ 50 & 30 & 30 & 25 \end{bmatrix} \cdot \begin{bmatrix} 1 \\ 1 \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} 6 \\ 0 \\ 80 \end{bmatrix}$,

$$ERed = \begin{bmatrix} 6 \\ 0 \\ 80 \end{bmatrix}$$

In this example ERed is the expected count of Red weapons at node *m* using the modal method. This weapon count will be used to compute Blue losses.

Let $BF_m := (0\ \ 10\ \ 0\ \ 60\ \ 0\ \ 0)$

denote the Blue force at node *m,* where Column 0=AV8B, 1=AH1W, 2=UH1N, 3=CH46, 4=CH53D, and 5=CH53E. This represents the planned number of assault forces arriving at node m, if the assault was executed. Note that this represents the expected number of survivors from engagements at other nodes on the path (route) before arriving at node *m.*

Let $BA_m := \left[BF_{m_{0,0}}\ \ BF_{m_{0,1}}\ \ BF_{m_{0,2}} \right]$ $\quad BA_m = [\,0\ \ 10\ \ 0\,]$

represent a subset of the Blue Force that can attrit Red at node m; in this case, AV-8B, AH-1W, and UH-1N (Cols 0-2). Note that only the AH-1W's (Col 1) are actually present in the assumed Red force.

Next,

$$BFA_m := \begin{bmatrix} .5 & .5 & .5 \\ 0 & 0 & 0 \\ .5 & .5 & .5 \end{bmatrix}$$

represents the fire allocation rules for the Blue force where Cols 0-2 (AV-8B, AH-1W, and UH-1N) are the Blue weapon platforms that can attack Red; the fire allocations must sum to 1 down any column. In the base case illustrated, all three systems will allocate fire equally between man-portable SAMs (row 0) and ZSU23-4s (row 2); no fire is allocated against S-60s since none are present in the assumed Red force (given in ERed).

The probability of kill matrix is computed from Equation (1), using the values in Table 5. The matrix displayed below represents values for daytime engagements for only the Blue weapon systems in matrices BA and BFA.

$$PDet_{Day} := \begin{bmatrix} .3 & .4 & .35 \\ .5 & .4 & .35 \\ .5 & .4 & .35 \end{bmatrix} \quad PHitGivenShot := \begin{bmatrix} .75 & .8 & .7 \\ .8 & .85 & .75 \\ .8 & .85 & .75 \end{bmatrix} \quad PKillGivenHit_{Day} := \begin{bmatrix} .225 & .32 & .245 \\ .4 & .34 & .263 \\ .4 & .34 & .263 \end{bmatrix}$$

Where the arrow indicates a "vectorize" operation (where vectorize refers to the multiplication between the elements depicted below):

$PKDay_{Blue} := \overrightarrow{\left(PDet_{Day} \cdot PHitGivenShot \cdot PKillGivenHit_{Day}\right)}$ (values taken from Table 5)

Thus

$$PKDay_{Blue} = \begin{bmatrix} 0.051 & 0.102 & 0.06 \\ 0.16 & 0.116 & 0.069 \\ 0.16 & 0.116 & 0.069 \end{bmatrix}$$

represents the probability of kill table for the three weapon systems represented in matrices BA and BFA. The columns are AV-8B, AH-1W, and UH-1N weapon systems against (rows) man-portable SAMs, S-60s, and ZSU23-4s.

Now that the Blue force has been specified, we can begin the adjudication process at node *m*. Recalling the order of combat (Blue attrites Red then Red attrites Blue), we must determine the expected number of Red kills (losses) prior to Blue kills (losses). At time *t*, where the arrow indicates a "vectorize" operation (here vectorize refers to the multiplication between the elements of the PK and BFA vectors):

$E_{BlueKillRed} := \overrightarrow{\left(PKDay_{Blue} \cdot BFA_m\right)} \cdot BA_m^{\ T}$. In this example,

$$E_{BlueKillRed} = \overrightarrow{\left[\begin{bmatrix} 0.051 & 0.102 & 0.06 \\ 0.16 & 0.116 & 0.069 \\ 0.16 & 0.116 & 0.069 \end{bmatrix} \cdot \begin{bmatrix} .5 & .5 & .5 \\ 0 & 0 & 0 \\ .5 & .5 & .5 \end{bmatrix}\right]} \cdot (0 \ \ 10 \ \ 0)^T = \begin{bmatrix} 0.51 \\ 0 \\ 0.58 \end{bmatrix}$$

Recall that $ERed = \begin{bmatrix} 6 \\ 0 \\ 80 \end{bmatrix}$ is the vector of assumed Red systems for this decision rule present at node m at time t = 0 (before attrition). Subtracting the vector of losses by Red to Blue at time t = 1 (when the attrition occurs) gives us the remaining forces at time t = 1:

$$ERed_{1} := ERed - E_{BlueKillRed}$$

$$ERed_{1} = \begin{bmatrix} 5.488 \\ 0 \\ 79.422 \end{bmatrix}$$

which represents the remaining Red weapon systems at node m at time $t = 1$ before adjudicating Red against Blue.

For the Red systems, showing only the three air-defense systems (columns) man-portable SAMs, S-60s, and ZSU23-4s against Blue aircraft (rows) AV-8B, AH-1W, UH-1N, CH-46, CH-53, and CH-53E (note that in all cases the numbers are the same for all Blue aircraft), we get:

$$PKillGivenHit_{Day} := \begin{bmatrix} .35 & .3 & .35 \\ .35 & .3 & .35 \\ .35 & .3 & .35 \\ .35 & .3 & .35 \\ .35 & .3 & .35 \\ .35 & .3 & .35 \end{bmatrix} \quad PDet_{Day} := \begin{bmatrix} .5 & .5 & .5 \\ .5 & .5 & .5 \\ .5 & .5 & .5 \\ .5 & .5 & .5 \\ .5 & .5 & .5 \\ .5 & .5 & .5 \end{bmatrix} \quad PHitGivenShot := \begin{bmatrix} .7 & .6 & .7 \\ .7 & .6 & .7 \\ .7 & .6 & .7 \\ .7 & .6 & .7 \\ .7 & .6 & .7 \\ .7 & .6 & .7 \end{bmatrix}$$

Then

$PKDay_{Red} := \overrightarrow{\left(PDet_{Day} \cdot PHitGivenShot \cdot PKillGivenHit_{Day}\right)}$ (values taken from Table 6)

where the columns indicate the Red systems against the Blue aircraft (rows). In this example,

$$PKDay_{Red} = \begin{bmatrix} 0.122 & 0.09 & 0.122 \\ 0.122 & 0.09 & 0.122 \\ 0.122 & 0.09 & 0.122 \\ 0.122 & 0.09 & 0.122 \\ 0.122 & 0.09 & 0.122 \\ 0.122 & 0.09 & 0.122 \end{bmatrix}$$

The Red Fire allocation is represented in the same manner as the Blue fire allocation:

$$RFA_m := \begin{bmatrix} 0 & 0 & 0 \\ .5 & .5 & .5 \\ 0 & 0 & 0 \\ .5 & .5 & .5 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}$$

Cols 0-2 (man-portable SAMs, S-60s and ZSU23-4s) are the Red weapon platforms that can attack Blue; the fire allocations must sum to 1 down any column. In the base case illustrated, all three systems will allocate fire equally; in this case, it is split only between AH-1Ws and CH-46s since they are the only ones present in the Blue force. We compute the attrition in the same way as we computed Blue against Red:

$$E_{RedKillBlue} = \overrightarrow{\left[\begin{bmatrix} 0.122 & 0.09 & 0.122 \\ 0.122 & 0.09 & 0.122 \\ 0.122 & 0.09 & 0.122 \\ 0.122 & 0.09 & 0.122 \\ 0.122 & 0.09 & 0.122 \\ 0.122 & 0.09 & 0.122 \end{bmatrix} \cdot \begin{bmatrix} 0 & 0 & 0 \\ .5 & .5 & .5 \\ 0 & 0 & 0 \\ .5 & .5 & .5 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}\right]} \cdot \begin{bmatrix} 5.488 \\ 0 \\ 79.422 \end{bmatrix} = \begin{bmatrix} 0 \\ 5.18 \\ 0 \\ 5.18 \\ 0 \\ 0 \end{bmatrix}$$

$$E_{RedKillBlue} := \begin{bmatrix} 0 \\ 5.18 \\ 0 \\ 5.18 \\ 0 \\ 0 \end{bmatrix}$$

which are the Blue losses to Red at node m at time period t = 1. Subtracting Blue losses gives us

$$BF_{m1} := BF_m - E_{RedKillBlue}^T \qquad BF_{m1} = [\,0 \quad 4.82 \quad 0 \quad 54.82 \quad 0 \quad 0\,]$$,

which represents the remaining Blue aircraft at node m at time $t = 1$ before advancing to node $m+1$.

This example illustrated the attrition calculations predicted at a node, using the modal method of summarizing the perception vector. In the following paragraphs the Three Largest (top three probabilities) and the Weighted Sum methods are discussed. The main difference is in the selection and number of the possible Red unit combinations with their associated perception probability. The unit combination matrix and perception vector that were used in the above example are used again for simplicity.

2. Three Largest Probabilities Method

This method uses the unit combinations that have the three largest perception probabilities. Once chosen, the top three perception probabilities are normalized. This normalized perception becomes the weighting factor used when calculating attrition to both forces. Using the values from the example above, the observation of forces perceived at node *m* are as follows:

$$\text{Possible unit combinatio ns} := \begin{bmatrix} 0 & 1 & 2 & 0 \\ 1 & 1 & 0 & 0 \\ 2 & 0 & 0 & 1 \\ 1 & 2 & 0 & 2 \\ 0 & 0 & 2 & 1 \\ 0 & 0 & 1 & 1 \end{bmatrix} \text{ with associated Perception } := \begin{bmatrix} .35 \\ .4 \\ .1 \\ .05 \\ .03 \\ .02 \end{bmatrix}$$

The largest three method would choose the following subset of the above vectors:

$$\text{Red}_{\text{Three Large}} := \begin{bmatrix} 0 & 1 & 2 & 0 \\ 1 & 1 & 0 & 0 \\ 2 & 0 & 0 & 1 \end{bmatrix} \text{ with perception} := \begin{bmatrix} .35 \\ .4 \\ .1 \end{bmatrix} \text{ and normalized} := \begin{bmatrix} .41 \\ .47 \\ .12 \end{bmatrix}$$

This new vector with its normalized perception ($\text{PNorm}_{\text{row}}$) is used when calculating attrition at node *m*. Each node in the potential route will have a "new" vector calculated from the top three combinations that will be used to determine the expected count of Red weapon systems (E[W]). Essentially, each row of the $\text{Red}_{\text{Three Large}}$ vector will run through the same attrition estimation process as in the mode method, except that the attrition to each side will be weighted by that rows corresponding normalized perception probability. Taking row 2 (1, 1, 0, 0) as an example, the expected losses from Blue would be the same as the modal example above except for the weighting of the result. Recall from the modal example above that:

$ERed = \begin{bmatrix} 6 \\ 0 \\ 80 \end{bmatrix}$ is the vector of Red systems present for this row at t=0 before attrition, but for the three largest method we weight this by the corresponding normalized probability ($PNorm_I = 0.47$ for this row). This yields the new expected Red weapon systems $ERed^T = [\ 2.82 \quad 0 \quad 37.6\ ]$. Using the simple attrition methodology defined previously,

${E_{BlueKillRed}}^T = [\ 0.51 \quad 0 \quad 0.58\ ]$ as before, which yields the new

$ERed_1 = PNorm_i * ERed - {E_{BlueKillRed}}^T$

$$ERed_1 = \begin{bmatrix} 2.31 \\ 0 \\ 37.02 \end{bmatrix}$$

This vector of expected surviving Red systems is then used in the same manner as above to attrit Blue. After attrition is computed for each unit combination (weighted by the normalized probability), the total expected attrition to Blue is the sum of the attritions. After this calculation is complete, "go / no-go" criteria are checked prior to departing to the next node, or mission complete if this node is the objective.

3. Weighted Sum Method

This method simply uses all of the possible unit combinations and their associated perception probabilities to calculate attrition of forces (recall that the test vectors are a subset of the 256 total possible unit combinations, which is why their perception does not sum to 1.0). All rows are used and no normalization of perception is performed. The perception becomes the weighting factor used when calculating attrition to both forces. Using the example above,

$$\text{Possible unit combinations} = \text{Red}_{\text{Weighted Sum}} := \begin{bmatrix} 0 & 1 & 2 & 0 \\ 1 & 1 & 0 & 0 \\ 2 & 0 & 0 & 1 \\ 1 & 2 & 0 & 2 \\ 0 & 0 & 2 & 1 \\ 0 & 0 & 1 & 1 \end{bmatrix}$$

$$\text{with associated Perception } (= \text{Weighting}) := \begin{bmatrix} .35 \\ .4 \\ .1 \\ .05 \\ .03 \\ .02 \end{bmatrix}$$

The attrition to each of the six unit combinations is computed as explained previously, weighted by the perception probability. The sum, which gives the expected attrition to Blue, determines whether the mission continues or not. Recall that Red's expected attrition is not used as an MOE because FEPM is only concerned with evaluating a single assault wave traversing over a potential route to an objective.

This example was used to illustrate the air-to-ground and ground-to-air adjudication process in the demonstration model and the differences among the three methods of predicting mission outcome under uncertainty. It is intended to educate the reader on how this model adjudicates combat at each node. Not all combinations were possible or practical in the example. However, the model uses all combinations (up to the software limitation) and all weapon systems (Blue and Red) engage each other during model runs. Finally, this example does not illustrate the air-to-air adjudication process that occurs at each node. This process is handled in the same manner as discussed above keeping in mind that Red's expected attrition is not used as an MOE.

IV. MODEL ANALYSIS AND RESULTS

This chapter discusses the analysis and results when the methodology presented in Chapter 3 was applied to the demonstration model (FEPM). The model was evaluated in two ways: software verification and behavior of the decision algorithms. The results are presented later in this chapter. Additionally, two measures of effectiveness (MOEs) were developed for evaluating the results of the decision algorithms: 1) how successful did the model predict mission outcome and 2) how far did this result deviate from the ground truth result. These two MOEs are shown in graphical displays throughout the chapter. Amplifying remarks are provided in the text as well as annotated in the graphical displays. Finally, the methods presented in this thesis are compared and recommendations are offered on their results.

A. METHODOLOGY

1. Why Test FEPM?

JWAEP does not currently have a model/module that addresses forced entry missions. Conceptually, FEPM offers a potential design that attempts to address the forced entry scenarios. The scenario chosen for this thesis was an amphibious air assault forced entry mission. If FEPM's methodology is to be incorporated into JWAEP, it must operate within the same parameters and methodology that JWAEP does; primarily the C^3I modeling that is supported by the presentation of perception derived from sensors. Because FEPM is a stand-alone model, this perception had to be artificially generated for testing. In JWAEP, a perception probability, simply defined, is the probability a certain force combination is on a given node/arc at a given time. Remember that FEPM takes (if implemented in software) a snapshot in time from JWAEP and evaluates a potential objective on that snapshot. The information that is provided by JWAEP is based on prior information (C^3I) that is updated continuously and is retained in its perception database. For FEPM to "work" within JWAEP, it must predict mission outcomes under these conditions (uncertainty). Therefore, FEPM's methodology had to be tested using uncertain perception probability vectors as inputs. When FEPM was tested, the perception probabilities had to be varied in order to mimic what JWAEP might input (a derived perception vector) to FEPM for a forced entry mission. The number of possible perception vectors that could be generated by JWAEP for a given ground truth force is infinite; only a few such vectors, chosen over a broad range of possibilities, can actually be used for testing.

2. FEPM Inputs

The FEPM model currently requires three inputs: Blue Forces, a potential route to an objective (containing Red unit combinations and their associated perception) and an automated run file.

The Blue Forces input file is a listing of the number and type of weapon platforms that Blue will be using on the mission. For this thesis, all Blue missions are amphibious air assaults and are equal in size to that of a Marine Expeditionary Forces' Air Component (Chapter 2). The number and type of weapon systems were determined from References 4 and 5.

Eventually, the potential route to an objective will be provided by JWAEP. For the stand-alone version of FEPM a planned route which represents ground truth (Table 10) and several variations of that route (Appendix) are provided as input files. The Red Units listed in Table 10 are the number of equivalent Soviet style Brigades (Regiments). The values in the table corresponding to the aircraft (MIG 23, SU 23, SU 27) are the actual number of weapon systems (before leakers) that will be seen at that node. A graphical representation of the Table 10 route is displayed as Figure 5. A flowchart of the automated run file is provided as Figure 6.

Node	Distance To next Node	INF	MECH	ARMOR	ADA	MIG 23	SU 25	SU 27
1	25	0	0	0	0	0	0	0
2	4	0	0	0	0	2	0	2
3	5	1	0	2	2	4	4	4
4	0	3	2	3	2	8	2	4

Table 10. FEPM Ground Truth Route Input File

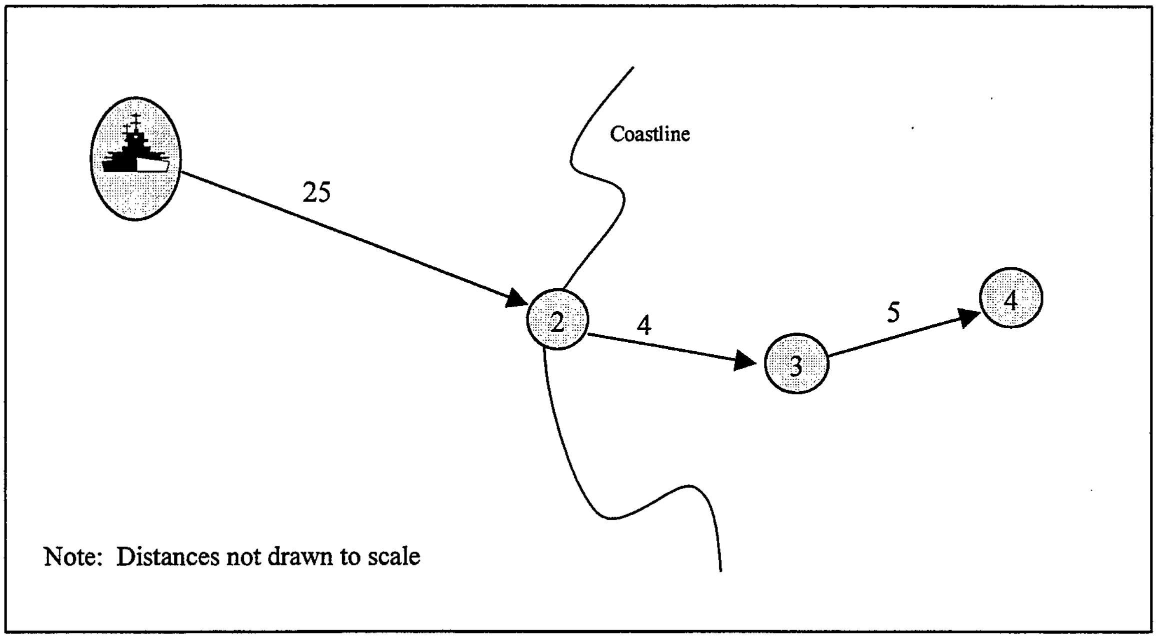

Figure 5. Planned Route to the Objective (Node 4) Used for Testing

Expanding on the discussion presented in Chapter III, recall that the goal of FEPM is to accurately predict mission success under uncertainty of perceptions as represented in JWAEP. To do this we must investigate the effects of different unit combinations with their associated perception probabilities (PS_m) and evaluate their effect on predicting mission success. For example, consider Node 3 on the simplified test database (Table 10). The ground truth vector at that node is:

$$\mathrm{GroundTruth}_3 := \begin{bmatrix} 1 \\ 0 \\ 2 \\ 2 \end{bmatrix} \quad \begin{bmatrix} \text{Infantry} \\ \text{MechInf} \\ \text{Armor} \\ \text{ADA} \end{bmatrix} \quad \text{with the unit type shown.}$$

As previously discussed, there are 256 possible combinations that JWAEP will determine a probability for. [Ref. 2] How do we know when to choose one vector over another for testing FEPM?

Before that decision can be made, we must consider the "goodness" of any particular set of perception vectors by considering two questions: is the perception highly certain (low uncertainty) and is the perception accurate (low bias)? To answer the first question, the reader is reminded that a set of vectors with low uncertainty assigns most of the probability mass to a single (unit combination) possibility. For example, consider the following subset of the 256 vectors, ranked in order of decreasing probability:

$$\text{Possible Unit Combinations} := \begin{bmatrix} 1 & 2 & 0 & 2 \\ 2 & 1 & 0 & 2 \\ 1 & 0 & 2 & 0 \\ 0 & 2 & 1 & 0 \\ 1 & 3 & 2 & 1 \\ 0 & 1 & 0 & 0 \end{bmatrix} \text{ with associated Perception} := \begin{bmatrix} .98 \\ .006 \\ .003 \\ .001 \\ .001 \\ .0005 \end{bmatrix}$$

This subset shows with high certainty (low uncertainty) that the first row of Possible Unit Combinations is in fact what the model "believes" is present at this node. All other rows are highly unlikely. Remember, the actual Possible Unit Combinations matrix has a total of 256 rows (6 shown), one for each possible combination of units. The first column is the number of infantry, the second mechanized, etc. The associated Perception Vector is sized accordingly (6 shown); each number represents the probability assigned to the likelihood that the associated unit combination is ground truth. A perception vector that has the highest uncertainty will assign an equally likely perception probabilities (1/ 256) to every unit combination, a rare situation in today's modern battlefield.

The next step for choosing one vector over another is deciding whether the perception of the unit combinations is accurate (low bias)? In the above example, the perception states that we are highly certain that ground truth is 1 Infantry, 2 Mechanized, 0 Armor and 2 ADA. Ground truth (GroundTruth_3) is actually 1 Infantry, 0 Mechanized, 2 Armor and 2 ADA. Thus, in this example we were highly certain but inaccurate. Looking closer at this result, we can see that the error was in the misclassification of the 2 Armor units as Mechanized Infantry, an error of type rather than total number.

To test FEPM, a set of possible unit combinations and perception vectors have been chosen which span three levels of uncertainty and bias (low, medium, and high) This generated nine possible combinations of uncertainty and bias, an example of which would be high uncertainty paired with low bias (for this test, a pairing such as this would be used for an entire route). In addition, special case vectors of certain ground truth, flat prior and a mixed combination were also used for testing. A more detailed explanation and complete listing of the unit combinations and perception vectors are contained in the Appendix.

2. FEPM Data Constants

Several data sets were hard coded into the FEPM demonstration model. They specifically dealt with combat adjudication (probability of kill tables in Chapter 3). If incorporated into JWAEP, these data sets would not be required due to JWAEP's large data sets and programs that are specifically designed to handle combat adjudication for large scale engagements of multiple weapon systems (ATCAL, COSAGE). The JWAEP data sets are able to factor in more variables when adjudicating combat than the data sets used for the FEPM demonstration model.

3. Data Collection

Data collection consisted of running the developed unit combinations and perception vectors (routes) through FEPM using the three decision rules during day and night operations. The data were transferred to an Excel spreadsheet to produce graphical displays, which are presented later in this chapter. The only limitations thus far were those found in the demonstration software (Pascal) which limited the number of possible unit combinations to 50 versus 256. This was determined to be an array size limitation with this version of Pascal. This limitation is not a factor in JWAEP nor is it a factor with the FEPM concept.

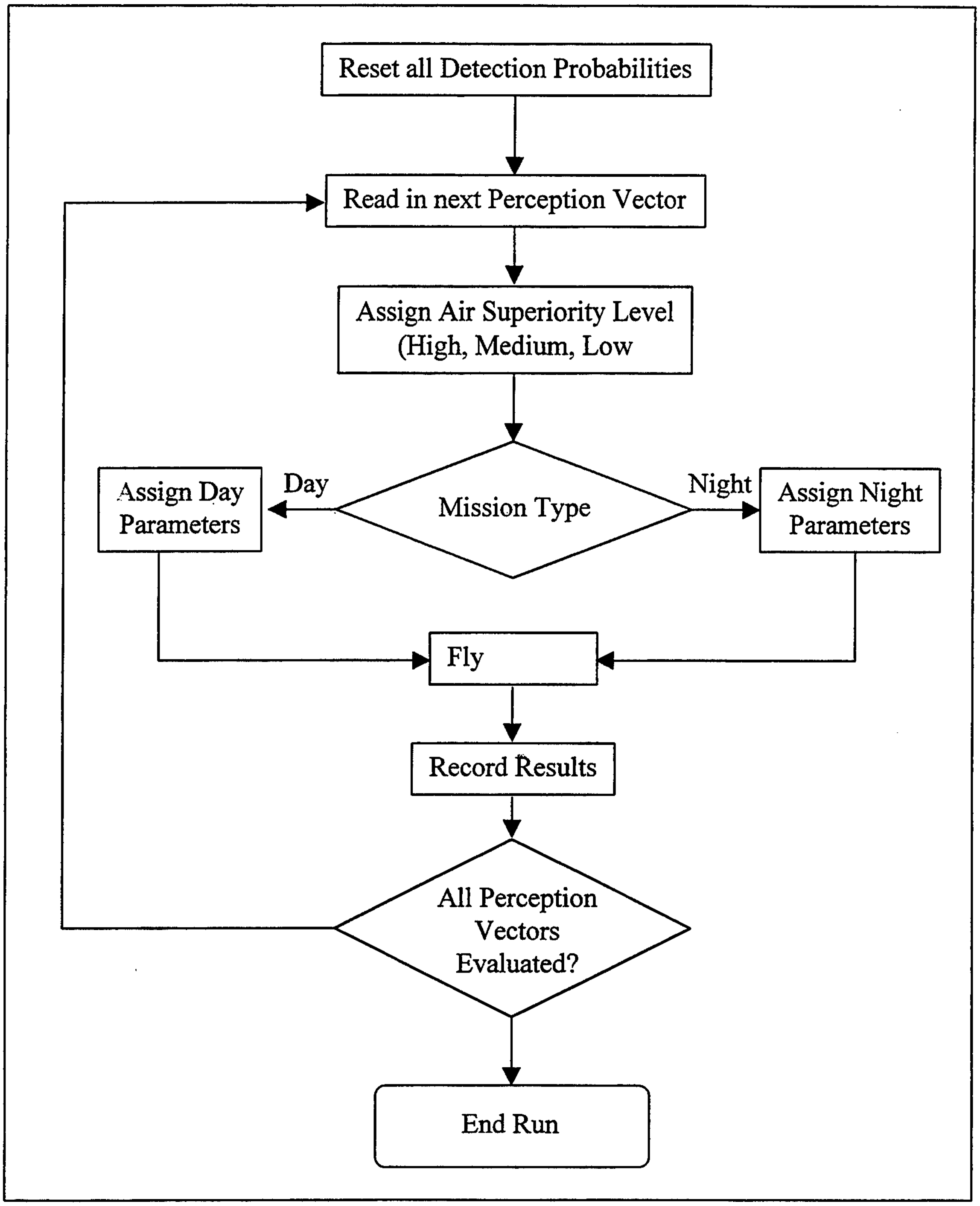

Figure 6. FEPM Run Procedure Flow Chart

B. FEPM TESTING

The testing of FEPM was performed in the two ways mentioned earlier (software verification and behavior of decision algorithms). The next two sections will discuss the results of these tests. It should be noted that these tests are not all inclusive and would require more comprehensive tests if FEPM were incorporated into JWAEP. The low air superiority level was used throughout for testing FEPM.

1. Software Testing and Verification

The goal of testing the software code was to determine whether or not the FEPM code was producing accurate results in terms of its deterministic attrition. This was performed in several ways. First, the basic code was designed for the Weighted Sum Method, which takes all of the unit combinations and their perception at every node. The code was then modified to accommodate the remaining two methods (Mode and Three Largest). The ground truth unit combination was run through all of the code (original and modified) and produced the same numeric result (total remaining blue ground forces) for all programs under day and night scenarios.

The next step in verification was to determine if the result above was in fact numerically correct. The ground truth unit combination was manually calculated and the result was within 3% of the model's result. This deviation is attributed to the round off error during these calculations. The round off criteria for the hand calculation was to round up at the second decimal place. Because of this, the hand calculations were slightly greater at each iteration, which accounted for the numerical discrepancy. This discrepancy between the models' result and the hand calculations was small enough to conclude that the models' results are accurate. Though this worked for ground truth (a single unit combination), it was necessary to verify each of the methods results with an actual data (one unit combination matrix and a perception vector).

The Node 3 low uncertainty vector and a low bias (highly accurate) unit combination matrix (located in the Appendix) were used. These data were run for each decision rule and their results recorded. Next, a manual calculation of the data set for each method was performed. These results were compared to the model generated results and were found to be within 3-5% of the manual calculations (3% for the mode and 5% for the others). This deviation was as before. From the results above, it was concluded that the model is producing the correct numeric results.

2. Measures of Effectiveness (MOE)

Now that the FEPM code has been verified in terms of producing accurate numeric results, how do the three methods perform under uncertainty? To answer this, two MOEs were developed so that the three methods could be compared. The first MOE addresses the question of how well did the model "predict" mission outcome under uncertainty? Simply put, did the model correctly decide what the outcome was – abort or reached the objective? To achieve this, the individual runs were compared to the end result in the ground truth run. If the model and the ground truth agreed, then the model predicted mission outcome successfully and vice versa. However, this MOE only addresses predicting mission outcome and not how far from ground truth the result was in terms of predicting the remaining Blue ground force size.

The second MOE addresses the above concern. It reports how close to the ground truth the computed remaining Blue ground force size was. The ground truth result provides the mission outcome and actual remaining Blue force size using the deterministic attrition methodology. The second MOE uses the computed expected remaining Blue force to compute the result as a percentage (plus or minus) from ground truth. A successful prediction using this MOE will occur if the model produced an expected remaining Blue ground force size that is within 5% of ground truth. This produces a range in which the model can have a successful prediction in terms of MOE 2, which may be in fact too strict for actual use.

These were the two MOEs chosen to evaluate each of the decision rules' performance under uncertainty. They are not intended to be all inclusive. They do address two key areas of FEPM and because of that, their use was considered to be reasonable and sound.

3. FEPM Run Results and Analysis

The run results and analysis focus on the three proposed methodologies for predicting mission outcome under uncertainty for amphibious air assaults in FEPM (Modal, Three Largest and the Weighted Sum of the developed vectors). The results are displayed graphically for each method under a day and night scenario. MOE 1, successful mission outcome prediction, is discussed in the text and is annotated on the graph using a "dashed" box with associated text where appropriate. The vertical (Y) axis is the percent deviation from the ground truth result and the horizontal (X) axis spans the levels of uncertainty (low, medium, high). The levels of bias (low, medium, high) are graphed for each level of uncertainty. For example, low uncertainty will have a low, medium, and high bias result graphed as will medium and high uncertainty.

Each of the following subsections addresses each of the chosen methods. A brief description is offered and is followed by the analysis of the results. An additional subsection presents the results of a mixed unit combination bias and uncertainty. The mixed case result shows how each of the methods perform when the route to an objective does not have the same bias or uncertainty at each node. The final section in this chapter discusses the special case of complete uncertainty. This section will draw on the conclusions presented in the weighted sum subsection. There is no quantitative data available for this special case (other than the results of the weighted sum method) due to the demonstration software's array size limitation. The reader is reminded that this is a not a limitation of FEPM or JWAEP.

The following terms, which are used throughout the subsections, are provided to the reader for clarity. The actual vectors and matrices are contained in the Appendix.

• Unit Combination Matrix - this is the 6 x 4 matrix of potential unit combinations that is a subset of the 256 possible unit combinations. There are three levels of bias (low, medium, high) that are used in the model. A low bias unit combination matrix is one where each entry in the matrix is near to the ground truth of that node (one entry in this matrix will contain ground truth). The medium bias unit combination matrix entries will range further from ground truth but not as much as the high bias unit combination matrix .

• Perception Vector – this is the vector of probabilities that a particular unit combination may be located at a particular node or arc. These probabilities have three levels of uncertainty (low, medium, high) that are used in the model. A low uncertainty perception vector masses the majority of the perception on a single probability with the rest being highly unlikely. Medium uncertainty has two or three probabilities in the perception vector that are larger than the rest and the high uncertainty perception vector probabilities will all be relatively equal.

• Unit Combination Set – this is the result of pairing a perception vector with a unit combination matrix. For example, a unit combination set would be a unit combination matrix and a low bias, low uncertainty perception vector (Low – Low). Depending on the method, one row or all of the rows of the unit combination set will be used. We expect the results for the low-low set to be the best where as the high-high set should be the worst in terms of both MOE's.

The ground truth results for each MOE are depicted in Table 11. MOE 2 is a single number rather than an expectation because deterministic attrition was assumed between the actual Blue and Red forces present; it represents the surviving ground personnel. Recall that the starting Blue ground force size is 2200 with a breakpoint value of 1100 (50%). The ground truth result for the night scenario is 1300 (denoted by the asterisk) which is above the breakpoint value. Based only on the total remaining force, we would expect to see "mission complete" vice "abort" for MOE 1. However, the helicopter escorts also have a breakpoint value of 40%, which was exceeded. Therefore the ground truth result for MOE 1 was to abort the mission even though the abort occurred at Node 4 – the objective. The value depicted in Table 11 for MOE 2 was calculated by multiplying the number of remaining transport helicopters by their associated troop carrying capacity (CH 53 = 30 troops, CH 46 = 15 troops).

Scenario	MOE 1: Mission Outcome	MOE 2: Remaining Blue Ground Forces
Day	Abort	497
Night	Abort	1300*

Table 11: Ground Truth Results

a. Mode Method Results

Recall that the Mode method will choose the unit combination with the largest probability. For our test cases, it chooses the row in the unit combination set that has the largest probability and runs that row through the model. If there exists a tie(s) in perception probability (uncertainty), the current decision logic chooses the first "largest" probability and its unit combination to run through the model. [2] Further, if a "flat" (all probabilities are equal, $PS_m = 1/256$) perception vector is observed by this method, the current decision logic does not allow the model to execute. The perception vectors and unit combination matrices contained in the appendix were formed into nine unit combination sets. These sets were then evaluated under a day and night scenario whose results are depicted as Figures 7 and 8. The mixed case result is presented separately in this chapter.

In general, the run results for this case (mode) of the nine "sets" in terms of MOE 1 predicted perfectly (all nine cases resulted in "mission abort"). For MOE 2, the results as depicted in the figures varied. Recalling the discussion above (plus or minus 5% of remaining Blue ground forces will be considered acceptable), the night results for these "sets" predicted accurately for MOE 2 as well as MOE 1, but the day results did not. Are these results reasonable? Why was there a lot of variability in the day results and very little for the night?

Recalling the composition of the test sets, we expect to see the best results for uncertainty to occur in the low case and the worst in the high case. The same can be said for bias. When combined, the best results should occur in the low-low pairing and the worst in the high-high pairing. What the figures show is that the results do not change over the levels of uncertainty when holding bias constant. This result was expected since the low, medium or high bias unit combination matrix does not change when the uncertainty (perception vector) changes for the test cases used. In fact, when holding bias constant, the same row of the unit combination matrix is picked over all three levels of uncertainty. When looking at the colored bars in the figures, the reader will see that the height of the bars with like color is the same over the levels of

2 This did not occur using the perception vectors tested (Appendix A) except for the special case of the flat prior.

uncertainty. Note that the low bias set result is the same as ground truth. Recall that the low bias matrix will assign a relatively high probability to the ground truth unit combination. In the test set (see the Appendix), the unit combination picked by this method will in fact always pick the ground truth combination.

In contrast, holding uncertainty constant and varying bias, we observe different results for each of the test bias sets. What was initially unusual was that for MOE 2 the medium bias result was further from ground truth than that of the high bias. Intuitively this does not make sense. However, after closer inspection it was determined that the Man-portable SAM Red weapon system dominated during combat over the other two types of Red weapon systems. In fact, by sheer chance the total number of Man-portable SAMs that Blue faced was just about the same for the low and high bias set, but were much less in number in the medium bias set. Therefore, the model did not attrit as many Blue weapon platforms in the medium bias set as it did in the low and high bias set. This demonstrates that the actual specific error in the bias is very important (e.g., is the bias in SAMs greater that ZSUs?), which probably does not allow us to generalize between "medium" and "high".

The observed difference in the day and night results in terms of MOE 2 (percent from ground truth) is a result of the deterministic nature of the attrition and the overall advantage to the attacker (Blue) at night. The Red weapon systems used are severely degraded at night where as the Blue weapon platforms are not as severely degraded. In fact two of the three Red weapon systems (Man-portable SAMs and S-60s) rely on visual identification and targeting. The other weapon system (ZSU 23-4) has radar tracking and targeting but when radiating, it becomes an instant target for anti-radiation seeking missiles. The severe degradation to Red at night and the more advanced Blue weapon platforms coupled with the deterministic nature of the attrition in the demonstration model make this day/night difference reasonable. What is important to note is that the pattern of the results is consistent between day and night.

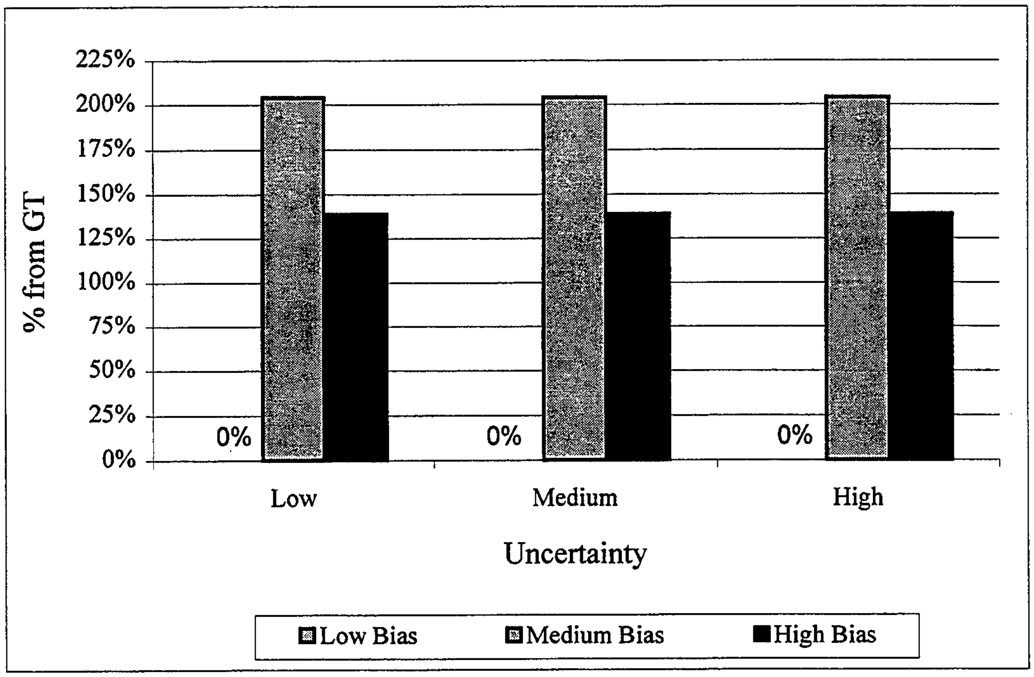

Figure 7. Modal Method Day Results

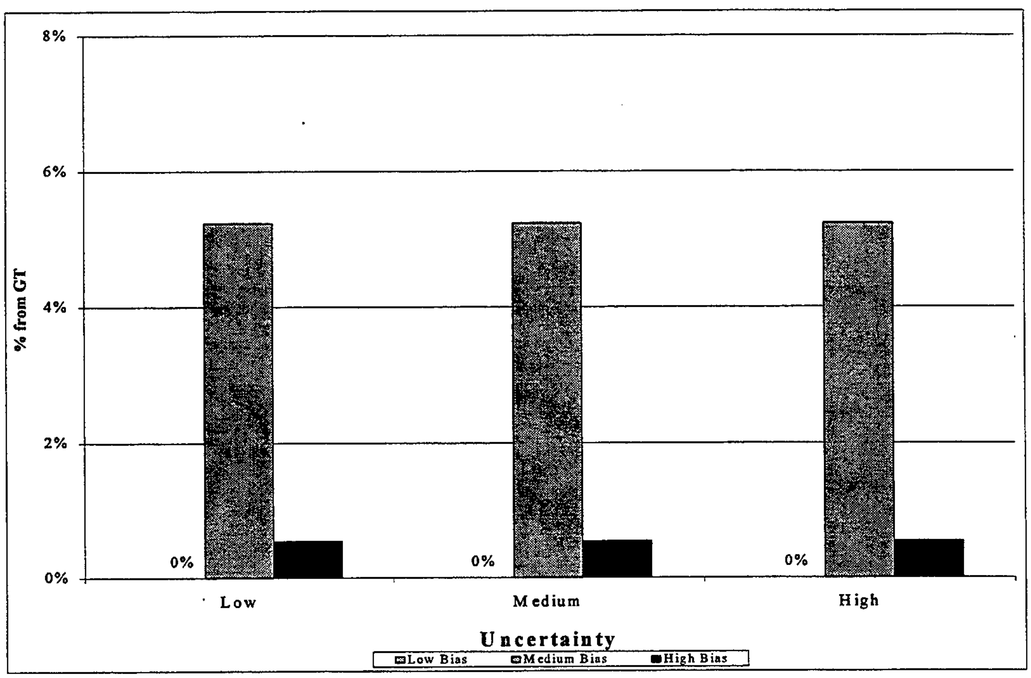

Figure 8. Modal Method Night Results

Thus far, the modal method appears to be sensitive to bias rather than uncertainty, due primarily to the composition of the unit combination matrices used in the test. The modal method appears to satisfy MOE 2 given the test sets. The results also show that the model tends to overstate the (expected) remaining Blue force size (MOE 2); this result is due to the deterministic attrition and the model's attrition sensitivity to Red's Man-portable SAM weapon systems. A preliminary conclusion would be that this method successfully predicts mission outcome but may significantly overestimate the remaining Blue ground force for a day mission. Additional test cases will need to be run to determine if this conclusion holds in general.

b. Three Largest Method Results

The Three Largest method chooses the largest three perception vector probabilities and the unit combinations associated with them. Following this, the method performs normalizes the probabilities on those choices so that they sum to one and computes the attrition for each of the three unit combinations. The normalized probabilities are used to weight the attrition from the unit combination to give the expected number of Blue survivors. The idea here is that there may exist a better chance of capturing the ground truth Red unit combination by choosing three combinations as opposed to one (modal method). However this method, as with the modal method, will not work for the "flat" (prior) case. The Three Largest method was tested with the same unit combination sets (Appendix A).

The results of the data runs, displayed in Figures 9 and 10, returned perfect MOE 1 predictions for the day and four incorrect predictions for the night. This result may be an indication that at higher levels of uncertainty more weight is placed on potentially "wrong" combinations; when coupled with higher bias, the result is an inaccurate prediction. This is especially true given the impact that the Man-portable SAM had on the previous results. MOE 2 results for the day, with the exception of the low bias set, were better than that of the modal method.

Building on the modal method results, we expect to see that uncertainty will play a bigger role in this method than in the mode method because more probabilities and their unit combinations are used. Choosing three probabilities instead of one should induce more variability for each level of bias and uncertainty. Referring to the figures, when we hold bias constant we observe different results for each uncertainty level. In the day scenario, we observe a slight upward trend in MOE 2 results as the level of uncertainty increases for each bias set. We would expect that as bias becomes higher the results could be further from the ground truth if we were able to test all of the combinations. The low bias set appears to have a gradual and fairly constant increase in percent from ground truth as it moves from left to right across the levels of uncertainty in both the day and night. This is a very logical result because this vector weights highest the unit combinations nearest ground truth. However, when examining the other two sets of bias (medium and high) we observe more variability and no discernable trend. Recall that these sets are allowed to be further from ground truth, which results in weighting more heavily the "wrong" combinations (combinations further from ground truth). Again we cannot generalize a trend with bias; it is very specific to the unit combinations chosen.

If we now hold uncertainty constant, we see from the figures that bias also plays a key role in MOE 2 type results. The day results show what might be called a "text-book" type of result. While holding uncertainty constant, as bias increases so does the percent deviation of predicted remaining Blue forces from ground truth. However at night time, with the exception of the medium uncertainty level, we observe somewhat unusual results. In the low uncertainty level, high bias yields the best results and medium bias the worst. The same is true for the high uncertainty level. The result is once again attributable to composition of the unit combination matrices (the Man-portable SAM situation).

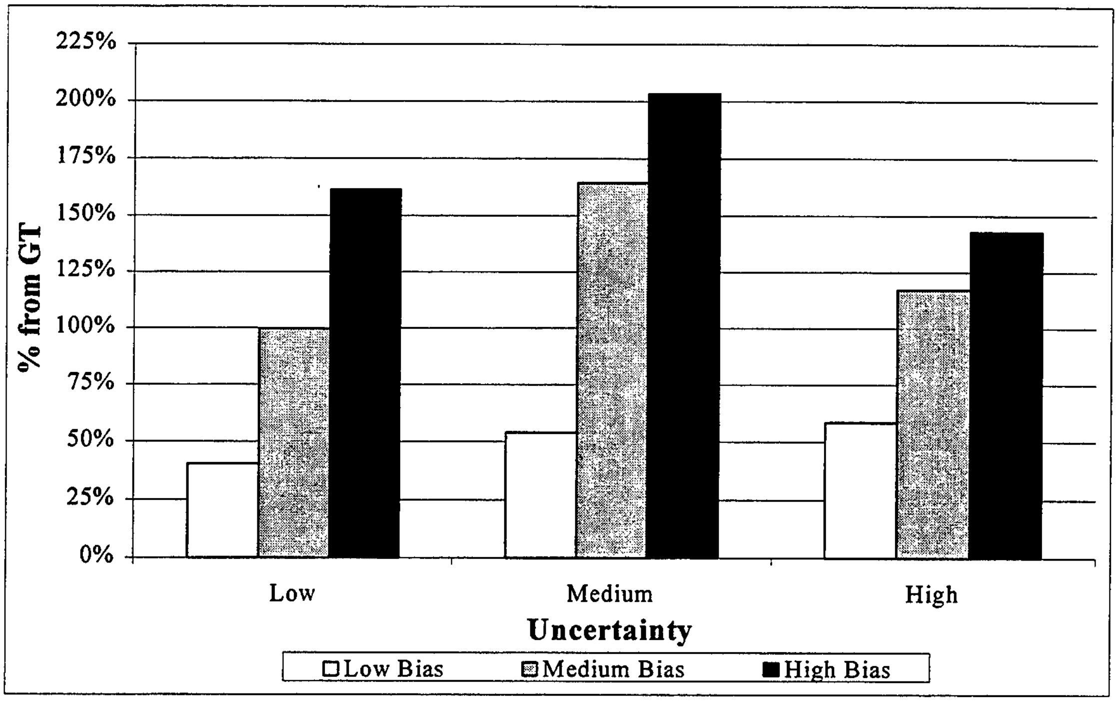

Figure 9. Three Largest Method Day Results

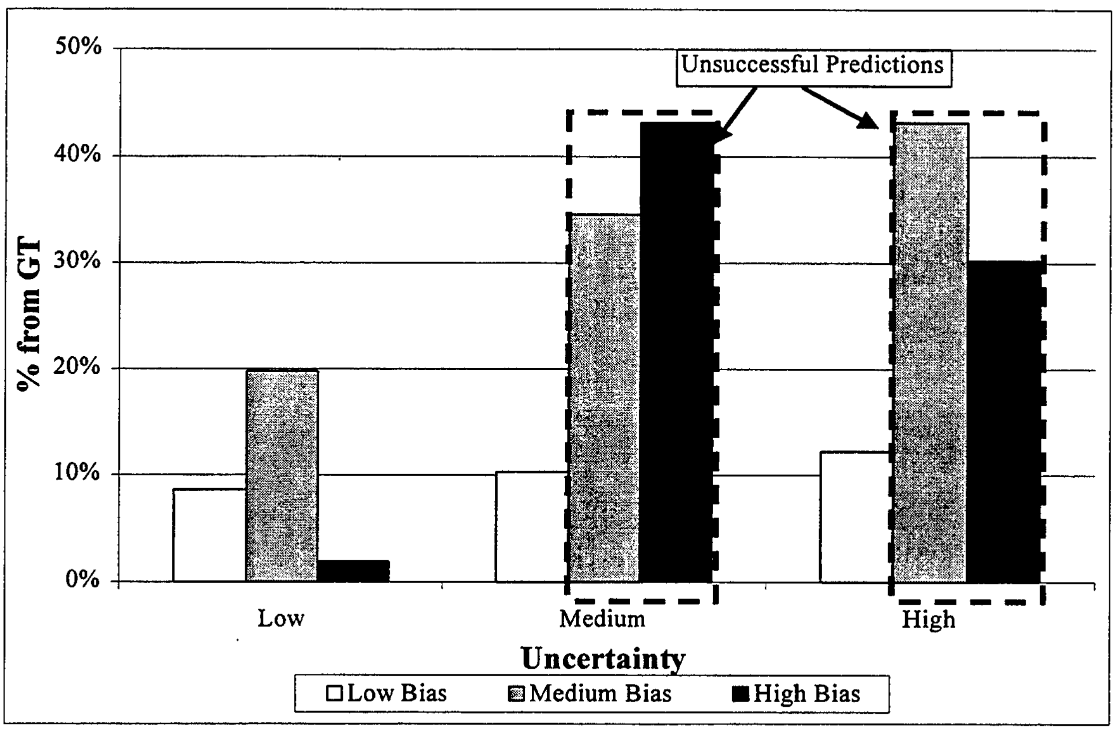

Figure 10. Three Largest Method Night Results

This method shows significant promise overall despite the MOE 1 failures at night which are attributable to the "made-up" test vectors. The method appears to be somewhat predictable in uncertainty, but not for bias. Similar to the mode method results, this method also overestimates the MOE 2 parameter of predicted remaining Blue ground forces. Given the limited scope of the tests so far, this method should be considered for more robust testing in the future.

c. *Weighted Sum Results*

The weighted sum method uses all the data from the unit combination sets (perception vector and paired unit combination matrix) contained in the Appendix. It uses the perception vector as a weight after all attrition is performed at each node using the corresponding unit combination. Unlike the previous two methods, the weighted sum method is the only one presented that can evaluate the special case of a "flat prior". However, evaluating this special case is currently not possible due to software limitations previously mentioned. Insight is offered on the potential performance of this method for the special case at the end of this section. The results of this method are discussed below and presented as Figures 11 and 12.

In general, this method did not perform well when considering either MOE 1 or 2. The entire night scenario was totally unsuccessful in predicting mission outcome (MOE 1) and two (medium and high bias at the medium uncertainty level) out of nine unit combination sets failed in the day. This result is explained by the makeup of the test data, specifically the medium uncertainty unit combination sets. As for MOE 2, the percentage from ground truth was the largest of the three methods tested on a level by level basis.

In keeping with the previous two methods, we would expect to observe increases for fixed levels of uncertainty as bias is varied, and increases for fixed levels of bias as uncertainty is varied. When bias was held constant, the results for the low bias set indicated a slight trend upward across the levels of uncertainty giving credibility to the above statement. The medium and high bias sets also increased across the levels of uncertainty but both peaked under medium uncertainty. A visual check of the unit combination matrices and perception vectors indicated that of the two perception vectors, the medium uncertainty vector weighted the top two rows more heavily than the remaining four rows whereas the high uncertainty vector was more evenly distributed. This resulted in weighting of unit combinations which were less than ground truth, thereby increasing the predicted number of remaining Blue ground forces (recall the previous discussions on Red weapon systems attrition effects on Blue).

Now, holding bias constant over the uncertainty levels should yield a general upward trend. What the figures tell us is that there is an upward trend. However, the medium uncertainty result is the highest of the three. Again, the medium uncertainty perception vector used in this test weighted the first two rows more heavily than the rest. This resulted in the medium uncertainty level to have the highest percent from ground truth than of the three decision rules tested for each bias set. This appears to be an artifact of the vectors chosen for the test rather a general trend.

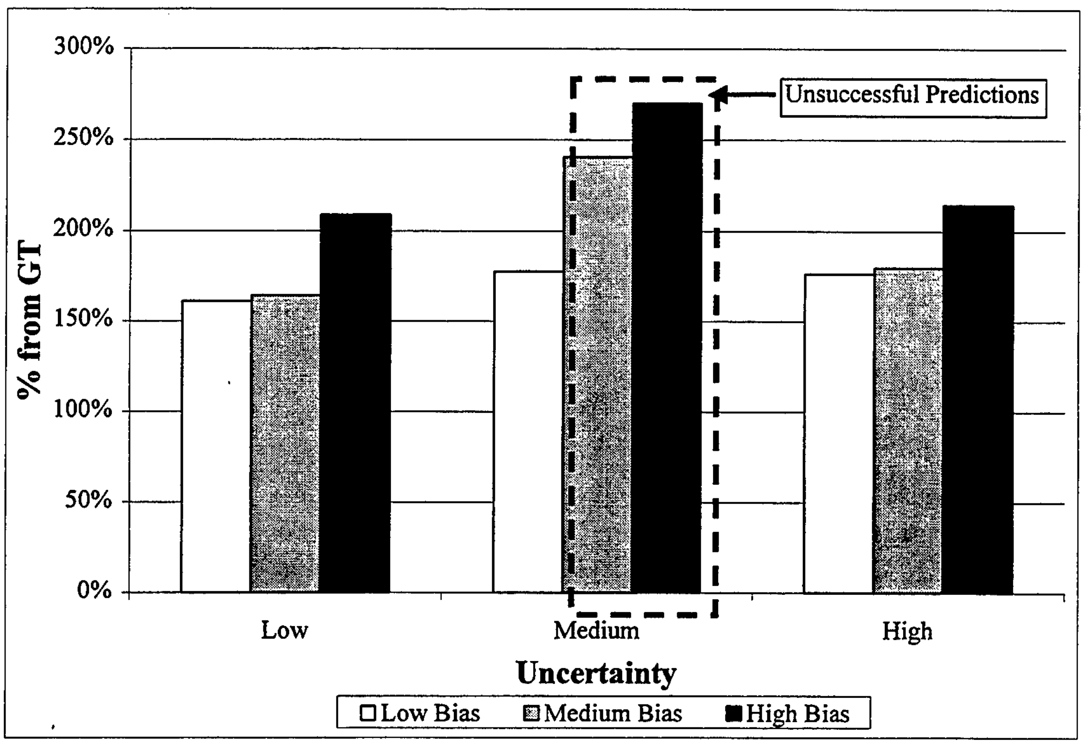

Figure 11. Weighted Sum Method Day Result

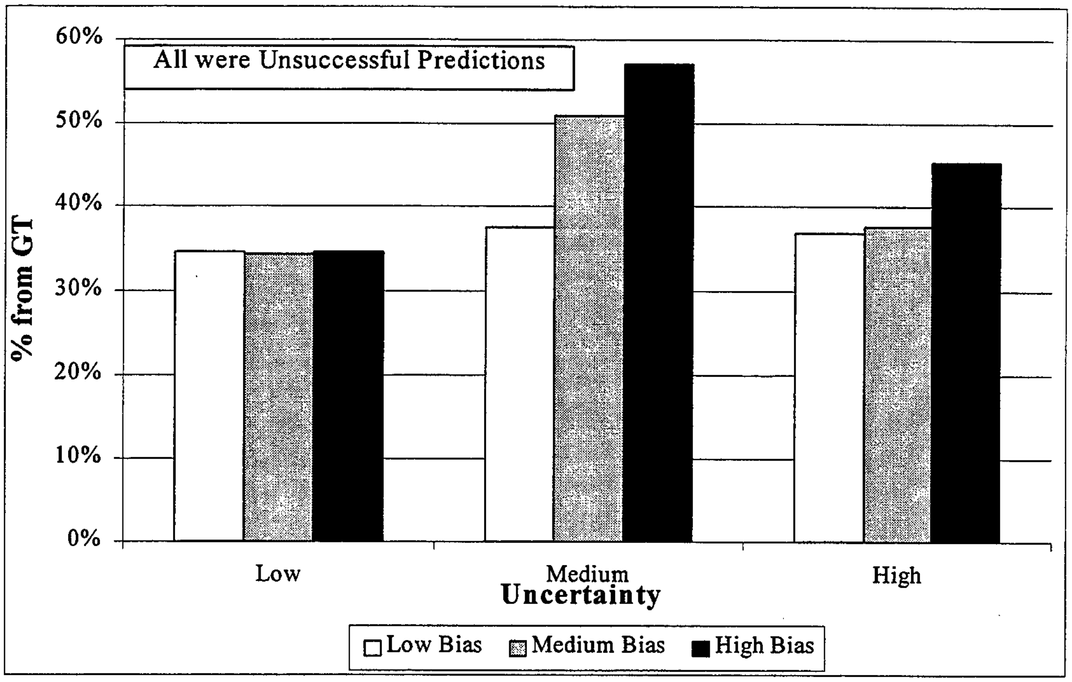

Figure 12. Weighted Sum Method Night Result

Taking the results discussed previously, we can attempt to apply what has been learned from this method and offer some insights on how this method would perform for the special "flat" case (perception is equal $PS_m = 1/256$ for all of the 256 possible unit combinations for this scenario). This case is nothing more than the full range of the high uncertainty perception vector and the high bias unit combination matrix. Using the above results, we would speculate that successful MOE 1 predictions for the day to be successful and the night to be unsuccessful. Further, we would also speculate that the percent from ground truth would increase from the ones depicted in the figures given the deterministic and limited ability of this demonstration model.

This method is sensitive to both uncertainty and bias, perhaps more so to uncertainty given the results. There were more unsuccessful predictions in terms of MOE 1 than the other two methods, but this result should not be a deciding factor when choosing which method is the best for predicting mission outcomes under uncertainty. More rigorous testing of this method as well as the others are required before a final decision on which method is the "best" for predicting mission outcome under uncertainty is made.

d. Mixed Combination of Uncertainty and Bias

Up till now, all of the nodes on the route tested had a specific uncertainty and bias level throughout. For completeness, a mixed combination of uncertainty and bias was developed and tested. This was accomplished by creating a route from the existing perception vectors and unit combination matrices. The route developed for testing is contained in the Appendix. Figure 13 provides the results of this "mixed" unit combination set.

The figure depicts the day and night results of the run. Recall that ground truth has not changed and the values in Table 11 still apply. The modal method predicted successfully (MOE 1) and the two others did not. The modal method's results are similar to the medium bias results contained in the mode section. Similarly, the Three Largest and Weighted Sum methods results for this case appear to be the same as their results in the medium uncertainty case. These results were influenced by the makeup of the mixed test route, specifically the medium uncertainty node chosen at random for this test. It appears that the medium uncertainty and its associated bias was the dominant factor in all of the results. This is attributable to the "made-up" test vectors. It is important to note that the reader should not be mislead by the modal methods performance when considering the two MOE's and is encouraged to review the discussion in that section.

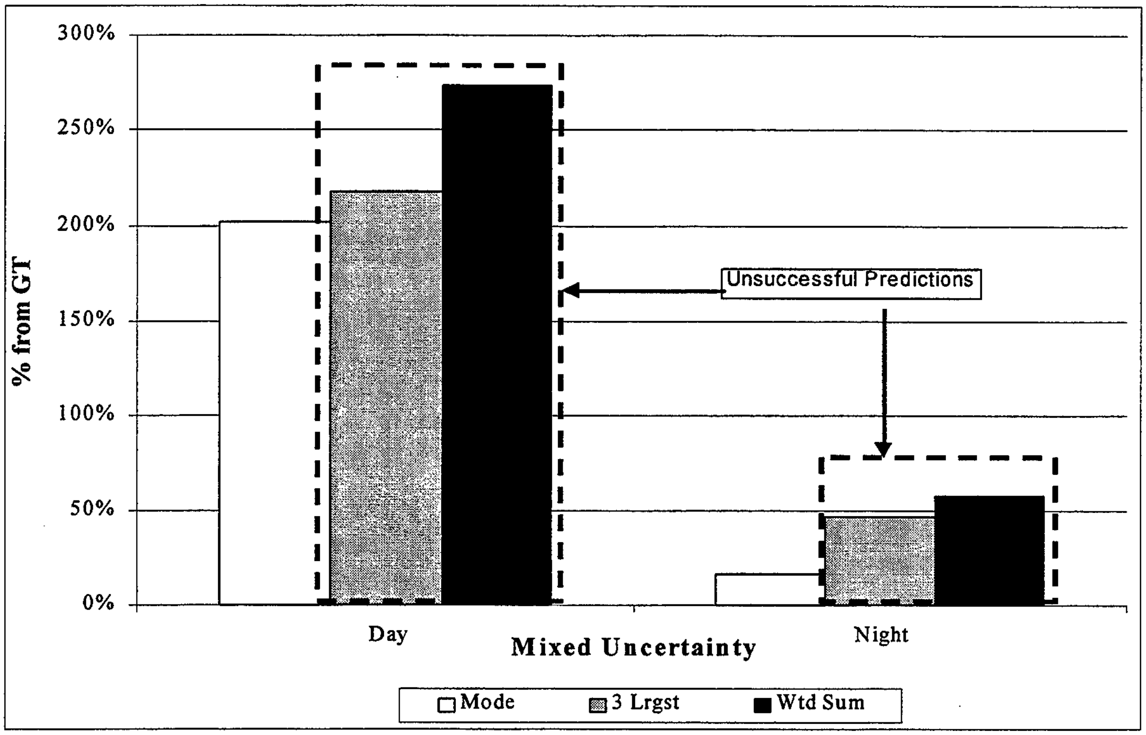

Figure 13. Mixed Accuracy and Bias Results

e. Overview of Results

Given the limited scope and deterministic nature of the demonstration model, none of the three methods can be ruled out at this time. The mode method did in fact perform the best (MOE 1), but picking a single probability and its associated unit combination could produce less than desirable results if the bias of the unit combination is anything less than low. Conversely, if we know what the bias is and if it is favorable (low) the modal method will predict accurately (MOE 1) regardless of the uncertainty level. In some cases, the mode method performed worse than the other two methods. The model, regardless of the method, overestimated the expected remaining Blue ground forces, especially during the day. This is an area that needs to be investigated in future research and may be moot given the sophisticated environment that JWAEP provides. The only other conclusion that is offered other than to investigate these methods more rigorously is that potentially all three of these methods could be used simultaneously on a node by node basis. Perhaps the logic could be an evaluation of the perception vector and if it has most of the probability massed on a particular combination then use the mode method. If two or three of the combinations are dominant then use the three largest and if there is an equal distribution of perception, then use the weighted sum. This hypothesis may in fact be the next step in testing FEPM.

V. CONCLUSIONS AND RECOMMENDATIONS

A. CONCLUSIONS

The analysis and results presented in Chapter IV indicate that the modal method performed the best in predicting mission outcome (MOE 1) under uncertainty. In terms of predicting the expected remaining Blue force size (MOE 2), the results are mixed among the three methods tested and appear to be dependent on the bias of the unit combination matrices. However, these results should not be considered conclusive by any means. This was a limited (small) test of the proposed methods, which needs to be expanded in order to cover the full spectrum of uncertainty and bias. The results also showed that bias had a profound effect on MOE 2 and that some methods handled bias better than others under the various levels of uncertainty. Because of this result, research into the bias of unit combination matrices is warranted and recommended. Finally, the model overestimated the remaining Blue force size which could also be attributed to the subjective nature of the test data. To rule out any of these methods at this time prior to more rigorous testing would be premature.

B. RECOMMENDATIONS

As stated above, these methods require more rigorous testing in the JWAEP environment. This will allow FEPM and the proposed methods to be subjected to a more detailed analysis in terms of uncertainty and bias to include the "flat prior" case. The significance of the bias effect and its relationship to the levels of uncertainty needs to be investigated. This effect is attributable to the subjective nature of the test data.

The amphibious air assault process used in the demonstration model followed current Marine Corps doctrine. It is flexible enough that when doctrine is changed, the model can change as well. Since the Marine Corps is continually refining its doctrine based on its mission requirements as set forth in the Defense Planning Guidance, it would be prudent to seek out Marines to ensure that the right doctrine is implemented correctly as JWAEP continues to develop. The agencies responsible for developing Marine Corps Doctrine are the Marine Corps

Combat Development Center (MCCDC) and the Commandant's Warfighting Lab (CWL) located at Marine Corps Base Quantico, VA.

Finally, the basic concept of this thesis (forced entry) needs to be expanded to address all types of forced entry scenarios. FEPM currently addresses only one aspect of forced entry, amphibious air assaults. There are two more major forced entry missions, amphibious sea assault and heliborne or airborne insertion. This will require a joint effort amongst all of the services to ensure that the missions are accurately portrayed in terms of doctrine and execution. That will require coordination with the appropriate doctrinal agencies within each of the services to accomplish this task so that these missions are accurately represented in future versions of JWAEP.

C. RECOMMENDATIONS FOR FUTURE RESEARCH

FEPM is in its initial stage of development. Only one forced entry mission, amphibious air assault, was addressed in this thesis. Research should be started into the other types amphibious assaults (sea, combined air/sea). Additionally, the Marine Corps is not the only service that will perform forced entry missions. JWAEP must also address the role of the Navy, Army, Air Force and Special Forces. The questions, "How do we model these forces?" and "Which one do we pick to perform the mission?" need to be answered.

For the Marine Corps portion of FEPM (amphibious assaults), the Navy's role is crucial to success in forced entry and must be addressed. In this thesis it was assumed that Red could not detect the Navy's movement into and in the Amphibious Operating Area. This may not be a realistic assumption given the current satellite and imagery technology of today. The Navy's contribution as a whole is very diverse and complicated. It is however, directly linked to Marine Corps Amphibious Doctrine. More integration of Naval Doctrine and Warfighting is necessary to present an accurate portrayal of their role in an MRC type conflict. If the Navy does not "get to the fight" , then a very large portion of forced entry is lost. This needs to be examined.

The results thus far have indicated that the bias of the unit combination matrices had significant effects on the results regardless of the subjectivity of the test data and its effects needs to be researched further. If there was a way to determine the bias of a unit combination matrix (vector in JWAEP), we would assign the best method to give us the best results for that bias. Currently we can determine bias on a unit by unit basis. What we do not know how to do is to come up with a single summary measure of bias across the probability vector associated with the matrix of all combinations, allowing us to compare one such matrix (with associated perception) with another. For example, if we had a unit combination with very low bias (high accuracy of the units that are present on a given node/arc), we would use either the mode or three largest method depending on the level of perception based on the test results to date. As bias increased we would opt for the three largest and weighted sum methods and if faced with a high bias case, the weighted sum method would be the most likely choice.

Finally, the special case where all of the perception probability are equal (flat prior) at a particular node or arc needs to be solved. The current approach would be to use the weighted sum method presented in this thesis. However, the interim solution may be as simple as a decision rule to wait for more information rather than a complex algorithm that attempts to determine the "right" answer.

APPENDIX. PERCEPTION VECTORS AND UNIT COMBINATION MATRICES

A. FEPM TEST ROUTES

The routes for the test cases are created from the sections below. An example of a test route would be low uncertainty perception vector and high bias unit combination matrix. This particular unit combination set (Chapter IV) would be used for all of the nodes present on that route. The values for this example are drawn from the individual sections below. Each section denotes a test node that has ten possible combinations. Within each section, the first entry is ground truth; the rest display the other nine combinations of uncertainty and bias, each having a range of low, medium and high. These nine combinations are shown in Table 1. The first letter indicates the uncertainty level and the second the bias level.

Route	1	2	3	4	5	6	7	8	9
Combination	L H	L M	L L	M H	M M	M L	H H	H M	H L

Table 1. Test Route Combinations of Uncertainty and Bias

Recall from Chapter IV that the uncertainty is modeled by values the perception probability associated with each unit combination at a particular node. In our test case we will use a 6 x 1 vector of probabilities (sized not to exceed the array limit of the demonstration software). A low uncertainty (highly certain) vector assigns most of the probability mass to a single entry, where as a high uncertainty vector will assign a more equal distribution to the entries in the perception vector. A medium uncertainty vector will be less certain than a low vector and more certain than a high one. All of these vectors are depicted in the following sections.

There are three levels of Bias for the test unit combinations (low, medium, high). A low bias vector will contain vectors very close to ground truth and for our test case will in fact contain ground truth. Conversely, a high bias vector will have vectors further away from ground truth and a medium bias will contain some vectors near ground truth and others that are not near ground truth. These matrices for the test cases have dimension 6 x 4 and are contained in the sections below. It is important to remember that these vectors were made-up for testing and were chosen to illustrate low, medium and high uncertainty and bias.

1. Node 2

Nodal perception and the associated possible unit combinations used in the test routes:

$$\text{Ground Truth} := \begin{bmatrix} 0 & 0 & 0 & 0 \end{bmatrix}$$

Perception Vector — Low; Unit Combination Matrices — Low, Medium, High

$$\text{Uncertainty} := \begin{bmatrix} .95 \\ .018 \\ .015 \\ .004 \\ .001 \\ .0005 \end{bmatrix} \qquad \text{Bias} := \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 1 & 0 & 0 & 1 \\ 1 & 0 & 1 & 1 \\ 1 & 0 & 2 & 0 \\ 2 & 0 & 0 & 0 \end{bmatrix} ; \begin{bmatrix} 0 & 0 & 1 & 0 \\ 1 & 2 & 0 & 1 \\ 0 & 1 & 0 & 0 \\ 2 & 0 & 2 & 0 \\ 1 & 2 & 0 & 0 \\ 0 & 0 & 1 & 2 \end{bmatrix} ; \begin{bmatrix} 2 & 0 & 1 & 0 \\ 0 & 1 & 2 & 0 \\ 0 & 0 & 3 & 0 \\ 1 & 0 & 1 & 0 \\ 1 & 1 & 1 & 0 \\ 0 & 2 & 1 & 0 \end{bmatrix}$$

Medium; Low, Medium, High

$$\text{Uncertainty} := \begin{bmatrix} .45 \\ .3 \\ .15 \\ .05 \\ .03 \\ .01 \end{bmatrix} \qquad \text{Bias} := \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 1 & 0 & 0 & 1 \\ 1 & 0 & 1 & 1 \\ 1 & 0 & 2 & 0 \\ 2 & 0 & 0 & 0 \end{bmatrix} ; \begin{bmatrix} 0 & 0 & 1 & 0 \\ 1 & 2 & 0 & 1 \\ 0 & 1 & 0 & 0 \\ 2 & 0 & 2 & 0 \\ 1 & 2 & 0 & 0 \\ 0 & 0 & 1 & 2 \end{bmatrix} ; \begin{bmatrix} 2 & 0 & 1 & 0 \\ 0 & 1 & 2 & 0 \\ 0 & 0 & 3 & 0 \\ 1 & 0 & 1 & 0 \\ 1 & 1 & 1 & 0 \\ 0 & 2 & 1 & 0 \end{bmatrix}$$

High; Low, Medium, High

$$\text{Uncertainty} := \begin{bmatrix} .3 \\ .25 \\ .2 \\ .15 \\ .05 \\ .04 \end{bmatrix} \qquad \text{Bias} := \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 1 & 0 & 0 & 1 \\ 1 & 0 & 1 & 1 \\ 1 & 0 & 2 & 0 \\ 2 & 0 & 0 & 0 \end{bmatrix} ; \begin{bmatrix} 0 & 0 & 1 & 0 \\ 1 & 2 & 0 & 1 \\ 0 & 1 & 0 & 0 \\ 2 & 0 & 2 & 0 \\ 1 & 2 & 0 & 0 \\ 0 & 0 & 1 & 2 \end{bmatrix} ; \begin{bmatrix} 2 & 0 & 1 & 0 \\ 0 & 1 & 2 & 0 \\ 0 & 0 & 3 & 0 \\ 1 & 0 & 1 & 0 \\ 1 & 1 & 1 & 0 \\ 0 & 2 & 1 & 0 \end{bmatrix}$$

2. Node 3

Nodal perception and the associated possible unit combinations used in the test routes:

$$\text{Ground Truth} := \begin{bmatrix} 1 & 0 & 2 & 2 \end{bmatrix}$$

Perception Vector — Unit Combination Matrices

Low: Low, Medium, High

$$\text{Uncertainty} := \begin{bmatrix} .97 \\ .01 \\ .005 \\ .004 \\ .001 \\ .0005 \end{bmatrix} \qquad \text{Bias} := \begin{bmatrix} 1 & 0 & 2 & 2 \\ 0 & 1 & 1 & 2 \\ 0 & 1 & 1 & 3 \\ 1 & 1 & 1 & 3 \\ 1 & 1 & 2 & 3 \\ 0 & 0 & 1 & 1 \end{bmatrix}; \begin{bmatrix} 1 & 0 & 1 & 3 \\ 1 & 0 & 1 & 1 \\ 0 & 1 & 2 & 3 \\ 1 & 2 & 2 & 3 \\ 0 & 1 & 1 & 3 \\ 1 & 2 & 1 & 2 \end{bmatrix}; \begin{bmatrix} 1 & 3 & 0 & 2 \\ 0 & 0 & 2 & 2 \\ 1 & 3 & 2 & 0 \\ 0 & 3 & 0 & 1 \\ 0 & 1 & 1 & 0 \\ 1 & 3 & 0 & 0 \end{bmatrix}$$

Medium: Low, Medium, High

$$\text{Uncertainty} := \begin{bmatrix} .5 \\ .3 \\ .1 \\ .05 \\ .03 \\ .01 \end{bmatrix} \qquad \text{Bias} := \begin{bmatrix} 1 & 0 & 2 & 2 \\ 0 & 1 & 1 & 2 \\ 0 & 1 & 1 & 3 \\ 1 & 1 & 1 & 3 \\ 1 & 1 & 2 & 3 \\ 0 & 0 & 1 & 1 \end{bmatrix}; \begin{bmatrix} 1 & 0 & 1 & 3 \\ 1 & 0 & 1 & 1 \\ 0 & 1 & 2 & 3 \\ 1 & 2 & 2 & 3 \\ 0 & 1 & 1 & 3 \\ 1 & 2 & 1 & 2 \end{bmatrix}; \begin{bmatrix} 1 & 3 & 0 & 2 \\ 0 & 0 & 2 & 2 \\ 1 & 3 & 2 & 0 \\ 0 & 3 & 0 & 1 \\ 0 & 1 & 1 & 0 \\ 1 & 3 & 0 & 0 \end{bmatrix}$$

High: Low, Medium, High

$$\text{Uncertainty} := \begin{bmatrix} .28 \\ .25 \\ .2 \\ .1 \\ .09 \\ .05 \end{bmatrix} \qquad \text{Bias} := \begin{bmatrix} 1 & 0 & 2 & 2 \\ 0 & 1 & 1 & 2 \\ 0 & 1 & 1 & 3 \\ 1 & 1 & 1 & 3 \\ 1 & 1 & 2 & 3 \\ 0 & 0 & 1 & 1 \end{bmatrix}; \begin{bmatrix} 1 & 0 & 1 & 3 \\ 1 & 0 & 1 & 1 \\ 0 & 1 & 2 & 3 \\ 1 & 2 & 2 & 3 \\ 0 & 1 & 1 & 3 \\ 1 & 2 & 1 & 2 \end{bmatrix}; \begin{bmatrix} 1 & 3 & 0 & 2 \\ 0 & 0 & 2 & 2 \\ 1 & 3 & 2 & 0 \\ 0 & 3 & 0 & 1 \\ 0 & 1 & 1 & 0 \\ 1 & 3 & 0 & 0 \end{bmatrix}$$

3. Node 4

Nodal perception and the associated possible unit combinations used in the test routes:

$$\text{Ground Truth} := \begin{bmatrix} 3 & 2 & 3 & 2 \end{bmatrix}$$

Perception Vector — Unit Combination Matrices

Low — Low, Medium, High

$$\text{Uncertainty} := \begin{bmatrix} .98 \\ .006 \\ .003 \\ .001 \\ .001 \\ .0005 \end{bmatrix} \quad \text{Bias} := \begin{bmatrix} 3 & 2 & 3 & 2 \\ 2 & 3 & 1 & 3 \\ 1 & 2 & 2 & 1 \\ 2 & 1 & 3 & 1 \\ 3 & 1 & 0 & 1 \\ 2 & 0 & 3 & 0 \end{bmatrix}; \begin{bmatrix} 3 & 1 & 2 & 2 \\ 2 & 2 & 1 & 3 \\ 1 & 0 & 2 & 1 \\ 2 & 1 & 0 & 3 \\ 1 & 1 & 0 & 0 \\ 1 & 3 & 0 & 0 \end{bmatrix}; \begin{bmatrix} 1 & 1 & 3 & 1 \\ 0 & 2 & 2 & 0 \\ 2 & 0 & 1 & 3 \\ 3 & 0 & 0 & 1 \\ 0 & 0 & 3 & 1 \\ 2 & 1 & 1 & 2 \end{bmatrix}$$

Medium — Low, Medium, High

$$\text{Uncertainty} := \begin{bmatrix} .55 \\ .25 \\ .1 \\ .08 \\ .005 \\ .001 \end{bmatrix} \quad \text{Bias} := \begin{bmatrix} 3 & 2 & 3 & 2 \\ 2 & 3 & 1 & 3 \\ 1 & 2 & 2 & 1 \\ 2 & 1 & 3 & 1 \\ 3 & 1 & 0 & 1 \\ 2 & 0 & 3 & 0 \end{bmatrix}; \begin{bmatrix} 3 & 1 & 2 & 2 \\ 2 & 2 & 1 & 3 \\ 1 & 0 & 2 & 1 \\ 2 & 1 & 0 & 3 \\ 1 & 1 & 0 & 0 \\ 1 & 3 & 0 & 0 \end{bmatrix}; \begin{bmatrix} 1 & 1 & 3 & 1 \\ 0 & 2 & 2 & 0 \\ 2 & 0 & 1 & 3 \\ 3 & 0 & 0 & 1 \\ 0 & 0 & 3 & 1 \\ 2 & 1 & 1 & 2 \end{bmatrix}$$

High — Low, Medium, High

$$\text{Uncertainty} := \begin{bmatrix} .25 \\ .2 \\ .18 \\ .15 \\ .1 \\ .1 \end{bmatrix} \quad \text{Bias} := \begin{bmatrix} 3 & 2 & 3 & 2 \\ 2 & 3 & 1 & 3 \\ 1 & 2 & 2 & 1 \\ 2 & 1 & 3 & 1 \\ 3 & 1 & 0 & 1 \\ 2 & 0 & 3 & 0 \end{bmatrix}; \begin{bmatrix} 3 & 1 & 2 & 2 \\ 2 & 2 & 1 & 3 \\ 1 & 0 & 2 & 1 \\ 2 & 1 & 0 & 3 \\ 1 & 1 & 0 & 0 \\ 1 & 3 & 0 & 0 \end{bmatrix}; \begin{bmatrix} 1 & 1 & 3 & 1 \\ 0 & 2 & 2 & 0 \\ 2 & 0 & 1 & 3 \\ 3 & 0 & 0 & 1 \\ 0 & 0 & 3 & 1 \\ 2 & 1 & 1 & 2 \end{bmatrix}$$

B. SPECIAL CASES

1. Mixed Uncertainty and Bias

This case takes the vectors and matrices presented above and for each node picks a different uncertainty and bias combination. These choices were combined to form an additional test route (case). The combinations chosen for this route are contained in Table 2. Again, the first letter indicates the uncertainty and the second bias.

Route	Node 2	Node 3	Node 4
Combination	L H	M M	H L

Table 2. Mixed Route Uncertainty and Bias Combinations

2. Flat Prior

The flat prior is a case where all of the perception probabilities are equal (1 / 256) for each possible unit combination. For this thesis, that number of possible combinations is 256. The vectors displayed below would be the same over any node that, for example had not had a sensor pass or just came in view to either force. The vectors depicted below will show the generic make up but will not be inclusive. The actual perception vector for these parameters would have dimension 256 x 1 and its associated unit combination vector would have dimension 256 x 4.

$$\text{Perception} := \begin{bmatrix} .004 \\ \bullet \\ \bullet \\ .004 \end{bmatrix} \qquad \text{Combination} := \begin{bmatrix} 0 & 0 & 0 & 0 \\ \bullet & \bullet & & \bullet \\ \bullet & & \bullet & \bullet \\ 3 & 3 & 3 & 3 \end{bmatrix}$$

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